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SOME PROBLEMS IN IRON ORE GEOLOGY IN SWEDEN AND IN AMERICA.

PER GEIJER.

During a long visit to the United States and Canada, in 1913, I had the opportunity to become acquainted with the geology of certain groups of iron ore deposits regarded by several observers as related to one or another of the principal iron-ore types of Sweden. The excursions that I made may have been brief in comparison to the complexity of the problems I intended to study, but the opportunities to discuss these problems—very often in the field—with the geologists engaged in solving them will go far to counterbalance this deficiency. The result is, in brief, that I have been able to contribute some new arguments to the discussion concerning the origin of the quartz-banded ores, just now a salient question in the study of ore deposits in Sweden and also in Norway, and that I have found that two metallogenetic provinces, one in the United States and one in Sweden, which have sometimes been compared to each other, show very remarkable analogies. These views have been presented to Swedish geologists in papers read before the Geological Society in Stockholm, and published in Swedish in its proceedings (*Geologiska Föreningens i Stockholm Förhandlingar*).[1] It is believed, however, that also the American geologists working with iron ores, will be interested to see what use can be made of their results for the solving of problems in another country.

[1] Vol. 35 (1913), pp. 439–483, and Vol. 36 (1914), pp. 157–173.

For my knowledge of American iron ores I am particularly indebted to Professor C. K. Leith, of the University of Wisconsin, Dr. D. H. Newland, of the New York Geological Survey, and Mr. G. W. Crane, late of the Missouri Bureau of Geology and Mines. The offer to take part in an "advanced students' excursion," under Professor Leith's guidance, gave the best possible opportunity to study the iron ore problem in the Lake Superior region; a visit in the company of Dr. Newland to some of the Adirondack mines gave me a good idea of the geology of that section, while the information previously given by Mr. Crane was of the greatest service to me during a brief visit to southeastern Missouri. The total number of the geologists whom I have to thank for kind reception and valuable help during my visit to the United States and Canada, is so great that I must abstain from enumerating them.

Apart from scattered deposits of titaniferous ores, bog and lake ores and some insignificant types, the iron ores of Sweden are divided into two geographically and geologically different groups. One district, generally known as central Sweden, comprises an immense number of deposits, mostly of small or moderate size, enclosed in highly metamorphosed Archean rocks.[2] The other district, in northern Lapland, north of the Arctic circle, contains fewer deposits, but among them some very large ones; the age is pre-Cambrian, but the metamorphism, though often strong, has not so largely veiled the primary characters of the ore-bearing rocks as is the case in central Sweden.

The ores of central Sweden are mostly low in sulphur and phosphorus, a fact from which the Swedish iron derives its old renown. The largest deposits, however, and all the more important ones in Lapland, contain a considerable quantity of apatite.

The two districts must be treated separately, as there are very important geological differences between them. It must also be pointed out that the present writer's position to the problems is

[2] While the American subdivision of the pre-Cambrian cannot be introduced for Sweden, it is certain that these rocks are at least as old as the Keewatin.

not the same in both cases: as regards central Sweden, the survey I am going to give will be a review of the results obtained by a great number of geologists, my own actual contributions having been very insignificant, while the discussion of the Lapland ores will be based mainly on personal experience.

A survey of the geology of the Scandinavian iron ores, intended for American readers, was given seven years ago by Professor Hj. Sjögren.[3] In view of the rapid advance in our knowledge of some ore groups during the last few years, however, and of the fact that the writer holds another view than Professor Sjögren on several important questions, it is necessary to give at least a brief review of the views of the Swedish geologists, before starting any comparisons between American and Swedish problems.

Broadly speaking, the ore-bearing district of central Sweden lies between lat. 59° and 61°. Large parts of this belt, however, are made up of gneisses which are generally barren. This is, for instance, the case in the western half of the province Värmland, which belongs to the great gneiss territory of southwestern Sweden. Generally, however, the Archean in the country between the two given latitudes is composed of two groups, the supracrustal[4] ore-bearing formation, and the granites. The latter are younger than the supracrustal formation, invading it as great masses that are generally classed as batholiths, although there is no possibility of definitely proving their batholithic nature. These granite areas are generally rounded, the rock being massive in the center, but more or less gneissic towards the margin of an area. Between them, the supracrustal formation forms narrow bands. On the whole, the relations between the two groups are essentially the same as is shown by the Laurentian and the Grenville in eastern Ontario, or the Laurentian and the Keewatin in the Lake of the Woods country.

It is now generally believed that the iron ores are older than the granites.

[3] "The Geological Relations of the Scandinavian Iron Ores," *Trans. Am. I. M. E.*, Toronto meeting, July, 1907, Vol. 38, pp. 877–946.

[4] The term *supracrustal* is used for rocks formed at the surface, as sediments, lava flows, and tuffs, while deep-seated rocks are called *infracrustal.*

The members of the supracrustal formation are hälleflintas, leptites, some gneisses, limestone and dolomite, mica schists (not common), and several types of iron ores. As the leptites are by far the most common rocks of the formation, it is generally called the leptite formation. The dip of the formation is generally very steep. As yet, no unconformities have been proved within it.

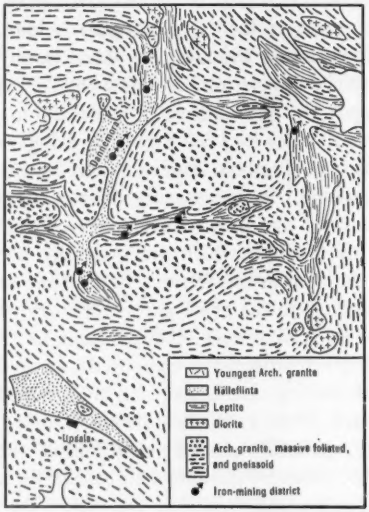

FIG. 43. Sketch map of the Archean in a part of the province Uppland. Scale 1 : 800,000. (After A. G. Högbom.)

The term hälleflinta has in Sweden long been used for quartz-feldspar rocks of a very fine grain (such as appear macroscopically dense) and conchoidal fracture. Many hälleflintas are acid volcanic tuffs (certainly in many cases silicified), consisting of fine ash or larger, once glassy fragments. Other forms consist of volcanic mud more or less mixed with normal sediments, and may grade into limestone. Some of these phases show a very regular stratification, best exemplified by the famous "banded hälleflinta" of Dannemora. In many cases, however, there is ample

evidence that the hälleflinta is a metamorphosed acid lava rock, with relic phenocrysts of quartz and feldspar.

In those pre-Cambrian districts in America that I have visited, real hälleflintas appear to be entirely absent. A dark green rock that occurs interstratified with the ironbearing formation at the old Mastodon Mine, near Crystal Falls, Mich., is the only hälleflinta-like rock I have seen. In part of the Piedmont region, however, hälleflintas must be important members of the volcanic series. Specimens collected by Messrs. Laney and Pogue, from the Gold Hill and Cid districts of North Carolina, that I saw in the Yale collections, indicate that the rocks of these parts show important analogies to those of central Sweden, even if they generally are less metamorphosed than the latter. The silicified tuff described by Pogue as "gunflint rock," is a most typical hälleflinta.

The leptites may be called coarse-grained hälleflintas or fine-grained gneisses, relations that suggested the once employed name hälleflint-gneiss.[5] They are, in short, crystalline schists consisting of feldspar, quartz and a moderate quantity of dark minerals, and differing from gneisses only by their finer grain. In many districts, the leptites can be shown to have originated from hälleflintas through metamorphism, and their original nature must, on the whole, be the same as that of the latter—lavas, tuffs, and tuffites (mixture of tuff material and normal sediments). Remnants of a porphyritic structure are common. A regular banding is often seen. By a higher degree of metamorphism, the leptites may change into real gneisses.

While the greater part of the leptites are lava rocks or tuffs, there are also undoubtedly among them many intrusive bodies, representing the more deep-seated phase of the volcanic activity. Some gneisses that are intimately connected with the leptites probably have the same hypabyssal origin.

[5] Leptite is an old term that was taken up again a few years ago. Previously, hälleflint-gneiss and *granulite* were used for these rocks. The former is rather unhandy, however, while granulite is used by French and German petrographers for various other kinds of rocks, which facts have caused the majority of Swedish geologists to return to the old term leptite.

The majority of the hälleflintas and leptites are acid rocks with a high percentage of quartz. The considerable part played by extremely sodic rocks is a remarkable feature. Very pronouncedly potassic types also occur, however, but are not so dominant. Amphibolitic rocks are common in certain districts, but their quantity is generally small in comparison to the acid rocks. Types of an andesitic or syenitic composition are rare.

Mica schists locally appear as members of the ore-bearing series, but are seldom conspicuous and do not, as a rule, contain any iron ore deposits. The most common rock of a distinctly sedimentary type is limestone (incl. dolomite). In some districts, there is a very regular alternation of beds of limestone and hälleflinta or leptite. In regions of stronger metamorphism, the limestone beds are often stretched and squeezed, the final result being a series of pitching lenses arranged *en échelon*. In petrographic characters, the limestone is similar to any crystalline limestone, such for instance as the Grenville limestones of eastern North America.

This very brief characteristic of the leptite formation gives the views embraced by the majority of the Swedish geologists. In recent years, however, attempts have been made to give another and radically different interpretation of these rocks. The author of this new theory is H. Johansson, who (for the first time in a paper published in 1906) explains the whole leptite formation, including limestones and the various types of iron ores, as deep-seated products of magmatic differentiation under mechanical influences. Johansson attacks the problem from several sides. Highly interesting are his contributions to our knowledge of the chemical characters of the ore-bearing rocks. Johansson finds the extreme differentiation in radically different chemical types, with a great scarcity of intermediate forms, to correspond better to the aspect of differentiation in deep-seated magma complexes than to that in series of surface extrusions, such as are known from younger geological systems. Another important argument is the close connection between the various types of iron ores, some of which are even by other authors regarded as magmatic, and the apparent relation between ore types and chemical character of the ore-bearing rocks. Recently, Prof. Sjögren has declared that he

shares Johansson's opinion of the leptites as a complex of deep-seated rocks.

When one thinks of the common occurrence of limestone in the leptite formation, sometimes in a regular, hundreds-of-times-repeated alternation with quartz-feldspar-rocks of an extremely fine grain never met with in a rock of a deep-seated origin, and many other features of this complex, it is difficult to understand how the same formation could be interpreted as a complex of abyssal intrusives. Though it is impossible to discuss the problem here in any detail, an important point may be emphasized. Those who regard the leptite formation as a supracrustal one, have started from districts where the metamorphism has been comparatively slight and it is possible to ascertain the original nature of the rocks. The existence of a series of intermediate stages allows the conclusion that other districts are built up of strongly metamorphosed equivalents of these rocks. Johansson and Sjögren, on the other hand, base their views on these latter districts.

It may well be that several of the facts pointed out by Johansson and Sjögren will cause some modifications of our views on the leptite formation, but in the judgment of the present writer, the conception of this formation as dominantly a supracrustal one is firmly founded on a wealth of evidence.

The iron ores of central Sweden occur almost exclusively in the leptite formation. There are several types, which in their typical development are very different from each other, but partly are connected through transitional forms. The main types are the following ones.

"*Apatite Ores.*"—This ore type has a characteristic and sometimes considerable apatite content. It is represented by a number of deposits within a rather limited area. Grängesberg, the largest iron mine of central Sweden, belongs here. Most deposits of this type are high-grade magnetites or hematites[6] with few gangue minerals except apatite. The ore bodies are more or less lenticular, and show clear contacts against their wall rocks, gener-

[6] By "hematite" is here always understood specular iron oxide.

ally leptites with some amphibolite. Some smaller deposits show an irregular, "schlieric" mixture of ore with a very high apatite content (up to 40 per cent.) and rock. On the whole, this group has many characteristics in common with the apatitic ores of northern Sweden (Lapland). It seems rather probable, that the apatitic ores of central Sweden are of an eruptive origin, but their present metamorphic state makes it almost impossible to trace the details of their geological history. It is worthy of note, however, that Johansson's views on the leptite formation are largely based on the detailed study of the apatitic ore district.

"*Limestone Ores.*"—These ores are high-grade magnetite bodies, occurring in the limestones of the leptite formation. Their characters in most cases strongly suggest a metasomatic origin. The magnetite is sometimes accompanied by a silicate gangue, whereby a transition is effected to the following type.

"*Skarn Ores.*"—The characteristic feature of these deposits is the association of magnetite with a gangue of dark silicates, pyroxenes, amphiboles, garnet, epidote, which is called "skarn." In many cases, the skarn ores occur in limestone, or in relations that make it probable that the ore and skarn mass has completely replaced a limestone. They are therefore by most authors regarded as metasomatic bodies, like the limestone ores, but the nature of the skarn further indicates that the replacement occurred under conditions of igneous metamorphism.

"*Quartz-Alumina Hematite Ores.*"—This ore type, which is not a very common one, comprises hematite ores with a moderate percentage of quartz and other rock-forming minerals, as feldspars or biotite. They are, on the whole, rather regularly bed-shaped, and are very intimately connected with their leptite wall rock, containing thin beds of it and grading into it. Some of the deposits of this type are closely connected with the apatitic ores of Grängesberg, and show a characteristic, though low, apatite content.

"*Quartz-Banded Ores.*"—These ores are mostly hematites, with an iron percentage of about 50, much more rarely magnetites. The type gets its name from the very regular lamination

by alternating bands of iron ore and quartz. The quartz is mostly gray, but sometimes a red jasper. In at least one ore body (Utö) one finds red jasper in those parts where the iron occurs as hematite, and gray quartz where it is in the form of magnetite. A little amphibole is often present. Garnet and epidote are not uncommon, and can often be plainly seen to be of secondary origin.

The origin of the quartz-banded ores is just now one of the most debated points in the geology of the ore-bearing formation of central Sweden. It is further of particular interest to American geologists, as these ores have often been compared to the "banded ironstones" of the Lake Superior region, and the results of American workers have been more or less directly applied to our problem.

All those who regard the leptite formation as mainly a series of supracrustal rocks, have been wont to look upon the regular banding of the quartzeous ores as a relic of sedimentary stratification. For Johansson and Sjögren, who believe in a deep-seated origin of the whole complex, such a view is, of course, excluded. Johansson has not defined his views beyond the general application of magmatic differentiation, as already outlined. Sjögren, in 1907–1908, proposed a general theory for all the various iron ores of central Sweden, regarding them as formed through aqueo-igneous solutions ranging in temperature from magmatic downwards. The apatite ores are believed to represent the highest temperature. Concerning the skarn and limestone ores, the theory is not so formulated that it must materially differ from the views given above as representative of the present general opinion on the case. The quartz-banded ores are also regarded as aqueo-igneous injections. Professor Vogt's views on similar deposits in northern Norway have also had influence on the discussion of the Swedish ores. The deposits in question are quartz-banded magnetites of a rather low grade, and are regarded by Vogt as magmatic segregations in granitic rocks.

The main arguments for a sedimentary origin are the following:

The regular layer shape of the ore bodies, where not too strongly deformed, and the regularity of the banding.

The identity in composition and structure with banded ironstones of known sedimentary origin.

The locally appearing regular alternation of ore and wall rock.

The view is old, dating from a time when all crystalline schists were regarded as some kind of peculiar sediments. For most geologists, however, the change in opinion regarding several fundamental questions in Archean geology has not caused any change of view on this point. To the arguments derived from the characters of the ore-bearing formation and the ores themselves is added the use of analogous, but less metamorphic ironstones as keys to the problem. In this respect, no other district has been in importance comparable to the Lake Superior region. The remarkable analogies between the banded ironstones of this district and the Swedish ores in question have been emphasized by many geologists, the most detailed discussion being that given by Sjögren more than twenty years ago.

Notwithstanding the radical change of opinion that is expressed in Sjögren's more recent views on the same subject, most of our geologists still feel convinced of the truth of his older views.

It is true that we have no siderite or greenalite rock, nor any "ferruginous chert," in Sweden. When we remember that even in the least metamorphosed districts (like Utö) the dip is now vertical, and the ore-bearing series shows signs of a very great mechanical deformation, this absence of rock types that are unstable under anamorphic conditions is very natural. The two main types arising through deep metamorphism of these forms, however, the quartz-banded crystalline hematites (jaspilites) and the corresponding, often amphibole-bearing magnetite rocks, differ from the Swedish ores only by their lower *average* iron content (about 25 per cent. compared to 45 or 50).

This analogy, at least with regard to the hematitic phases, has formed the main basis for comparisons between the two metallogenetic provinces, but in spite of all descriptions I was surprised to find how complete it is.

Forms with gray quartz and finely granular hematite are represented for instance by the Striberg and Norberg mining districts in Sweden, and by phases of the Vermilion jaspilite. Hematite

with bands of red jasper is the main type of the ore at Utö and the typical development of the Marquette jaspilite. Ore with micaceous hematite is not uncommon in Sweden and closely resembles a certain type from the Marquette Range, and a phase of the Traders bed at Iron Mountain, Menominee. As to the iron content, it must be remembered that there are many ore bodies in Sweden that do not range higher than the richer parts of the Lake Superior iron-bearing formations.

The analogy between the magnetic phases has not received the same attention. In Sweden, ores of this type are not common, but northern Norway contains large deposits which, as already stated, have to be considered when discussing their Swedish counterparts.

Magnetite alternating with gray quartz is a subordinate phase of the Utö ore body, the bulk of which is a hematite with bands of red jasper. These relations suggest as a probable explanation that the magnetic ore represents the parts that were not oxidized before anamorphism, while this had been the case with most of the ore.

Concentrations of rich, not banded ore are sometimes, but only rarely, met with in the Swedish mines operating on quartz-banded hematites. It seems quite probable that the origin of these high-grade bodies is essentially the same as that of the workable ores of the Lake Superior country. This was also suggested by Sjögren in his first articles.

While thus the petrographic analogies between the Swedish and the American "banded ironstones" leave little more to be desired, the geological association is not the same in both cases. Sjögren and Johansson find this difference so important as to completely outweigh the common features of the two districts. These authors claim that even if the leptite formation were of supracrustal origin (which, in their opinion, it is not), its dominantly acidic-volcanic nature so strongly contrasts with the sedimentary Huronian series with their slates, quartzite and dolomite, that every comparison is absurd. If we leave the Huronian out of discussion, however, and compare the leptite formation to the Keewatin only, the difference is not so marked. Both series are mainly

volcanic, with little normal sediments save the iron-bearing formations. There is still a great difference, however, inasmuch as the Keewatin volcanics are femic rocks (metabasalts), but the leptites are salic rhyolites. Yet it is noteworthy that rhyolite rocks occur as members of the Keewatin volcanic series and sometimes show the same close relations to the iron-bearing sediments as do the metabasalts.

According to Johansson and Sjögren the champions of the sedimentary theory overrate the value of the banded structure as a proof of sedimentary origin. It is true that the old idea of the banding as due to annual climatic variations can hardly be upheld any more, but the train of thought nowadays is different, emphasizing the absolute similarity to structures of proved sedimentary origin and the absence of any really analogous phenomena in bodies of another origin.

The discovery of quartz-banded ores similar to those of central Sweden, and of magmatic origin was announced some years ago, and was brought forth as an extremely weighty argument against the sedimentary theory. These ores occur in northern Norway. Scattered deposits appear in the mountainous Lofoten Islands, but the largest ones are much further east, at Sydvaranger close by the Russian frontier line. Professor Vogt has described the Lofoten deposits as magmatic segregations in a schistose granite and believes them to have been formed in essentially the same way as the segregations of titaniferous iron ore in gabbro and anorthosite. Later, Vogt has applied the same views to the Sydvaranger district, regarded by him as one of the clearest cases of iron ores formed through magmatic segregation in acidic rocks. Professor Sjögren, who visited the Lofoten district only, arrived at a somewhat different conclusion. He found the immediate wall rock to be similar to the Swedish leptites, but to appear to grade into a real granite. Further, he describes intrusive contacts between ore (younger) and the wall rock. Sjögren concludes that the ore magma has been injected, in a state of aqueo-igneous fusion, the leptite rock being a granite altered through contact metamorphism. If the facts in the field did not allow any other interpretation, one would not have any right to

deny the existence of magmatic intrusive quartz-banded iron ores. Sjögren himself states, however, that his observations were made during hasty visits to the various mines, and no drawings or maps illustrating the contact relations are given. We may therefore be allowed to await more detailed data before taking any definite position. A skeptical attitude is also fully justified by the properties of the other Norwegian district of the same kind, Sydvaranger.

During a visit to this district, I was totally unable to find any proof of an eruptive origin of the deposits. Neither of the two hypotheses—Vogt's and Sjögren's—proved satisfactory. The ore-bearing rocks are leptitic, though partly more coarse-grained than the typical Swedish leptites. Among them are forms with a composition hardly ever found in igneous rocks, as types combining a high quartz content with a calcic plagioclase. There are no intrusion phenomena visible anywhere at the contacts of the ore bodies. The ore shows an exceedingly regular banding of magnetite and quartz. These facts caused me to express the opinion that the ores are highly metamorphosed chemical sediments.

While aware of a great resemblance between the Sydvaranger ore and some types of banded ironstones in other districts, including the Lake Superior region, I had no idea that the analogies to the latter are so complete as I have found afterwards.

The Sydvaranger ore has an average iron content of about 36 or 37 per cent. The mineral constituents are magnetite, quartz, and a light green amphibole. The amphibole is more common in the magnetite than in the quartz bands. Now and then there appear amphibole bands with only a little magnetite, and locally such bands take the place of those of magnetite throughout a small ore body. Garnet and diopside have been noted in one small ore body only. Within a limited area, a dark green hornblende takes the place of the quartz bands. The occurrence of an inclusion of quartz-banded ore makes it practically certain that this hornblende has been formed through the replacement of the quartz bands.

Among the iron-bearing formations in the Lake Superior region proper, the one most similar to Sydvaranger is the Negaunee of Marquette, when anamorphosed, as near Michigamme. In mineralogical composition—including iron content—and in regular-

FIG. 44. Quartz-banded magnetite, Sydvaranger, Norway. (Length of hammer shaft 60 cm.)

ity of banding, the analogy is complete. The only slight difference lies in the degree of metamorphism, the quartz bands of the Negaunee formation being frequently fractured during the folding, while the Sydvaranger ore shows the soft folding of the "rock flowage" depths. It is worth noticing, that the Negaunee formation locally shows the banding of amphibole and quartz also sometimes found at Sydvaranger.

The Keewatin iron-bearing formation of Moose Mountain, Ontario,[7] shows even greater resemblance to that of Sydvaranger,

[7] The writer visited this district as a member of the C 6 excursion of the 12th international geological congress, under the guidance of Dr. W. G. Miller.

the degree of metamorphism being also the same. The banding of magnetite and quartz, with more or less of a light green amphibole (chiefly in the magnetite bands), the iron content, the extremely strong folding, generally without fracturing, make the ore of Moose Mountain *identical* in the present conditions to that of Sydvaranger. Also at Moose Mountain there appears a phase with bands of dark green hornblende instead of quartz, and, by a curious coincidence, containing an inclusion of quartz-banded ore, which differs from the one described from Sydvaranger only through the fact that the replacement of quartz through hornblende is more evident.

The epidote, which accompanies part of the high-grade ore at Moose Mountain (Mine No. 1), at least partly replaces quartz (or secondary hornblende?). Unfortunately, the few hours at my disposal did not permit more than a very superficial study of this ore variety, which may have no counterpart in Sydvaranger, where epidote appears but, so far as I know, never in such quantities.

In view of all these analogies, I think there is very good reason for believing the geological history of the Sydvaranger ores to have been in all important points the same as that of the Moose Mountain iron-bearing formation, which is clearly of the Lake Superior type. As the Lofoten deposits probably are analogous to those of Sydvaranger, and are so described by Vogt, they cannot be accepted as proved cases of magmatic quartz-banded ores. As yet, therefore, no deposit of quartz-banded iron ore of undeniably magmatic origin has been found.

In the ore-bearing district of northern Lapland, as in Central Sweden, the pre-Cambrian consists of supracrustal rocks and large masses of deepseated intrusives. It is possible that the large intrusions partly are older than all the supracrustal rocks and partly intermediate in age between two subdivisions of them. The nature of the country, the deep and continuous drift mantle, and other causes have hampered stratigraphical and structural work, some of the main features in the geology of this region thus being still not definitely known. As in central Sweden, ore

deposits occur in the supracrustal rocks only. Volcanic rocks predominate in the form of lava flows, tuffs, and hypabyssal intrusions. The normal sediments, phyllite and quartzitic sandstone, are the youngest among the supracrustal rocks, and may possibly rest unconformably on the older, dominantly volcanic complex.

The bedded rocks generally have a very steep attitude, nearly vertical dips being common. From reasons already given, the structure has hitherto been only very incompletely deciphered. The degree of metamorphism is widely varying. At Kiruna, for instance, the volcanic rocks partly exhibit well preserved microtextures. In other districts, the phenocrysts of the porphyries remain intact, but the groundmass is recrystallized (the rock thus resembles certain leptites) while at Gellivare, about 60 miles south of Kiruna, the metamorphism has proceeded so far as to render the volcanic rocks gneissoid.

The volcanic series has a chemical character rather different from that of the leptite formation of central Sweden. Rocks of a syenitic or quartz-syenitic composition are probably most abundant, but metabasalts appear in great quantities in certain districts. The metabasalts sometimes show ellipsoidal parting. Their plagioclase is a pure albite, a most remarkable feature that is ascribed to secondary processes. There are no ores in the metabasalts, all deposits occurring in porphyries of a syenitic or quartz-syenitic character. In by far the most cases, these rocks show a distinctly effusive texture, although lack of exposures may make it impossible to decide whether they really are surface flows, or intrusions at shallow depths. Sometimes, even when there is a practical certainty that the magma has actually been extruded at the surface, there is a gradual downward transition from phases with a volcanic texture to a fine-grained syenite. The best known case of this kind is that of the foot-wall rock of the Kiirunavaara ore body. It seems possible, that some eruptions have been subaquatic, which may account for this and some other puzzling geological and textural relations.

The ore-bearing rocks are classed as syenite-porphyries[8] and quartz-porphyries.[8]

The syenite-porphyries have a silica percentage of about 55 to 60. They are mostly sodic rocks. The most common dark silicate is a diopsidic augite, very often changed to amphibole (*i. e.*, uralitized). Magnetite is an important constituent and mostly surpasses the dark silicates in quantity. In some phases it forms 30 to 50 per cent. of the rock, the rest being a nearly pure albite feldspar. This type has been called magnetite-syenite-porphyry.

A very characteristic feature of the syenite-porphyries, notably at Kiruna, is the common occurrence of rounded cavities more or less completely filled with hornblende, magnetite, apatite, titanite or feldspar. These aggregates, which apparently are not directly comparable to quartz or calcite amygdules, have been called nodules, in order to get a handy and neutral term. Professor Bäckström, the first geologist who undertook a systematic study of these nodules, found their minerals to be probably of a pneumatolytic origin. His explanation was, that the already solidified porphyries were permeated by gaseous solutions coming from the same source as the rocks, and depositing their content of certain constituents as fillings in vesicles. The writer, while largely agreeing with Bäckström in considering the nodules as "pneumatolytic" bodies, has found what seems to be conclusive evidence that the material of the nodules was gathered through a sort of lateral secretion *during* the crystallization of the rock, the volatile constituents, which through their mechanical action caused the development of the blowholes, having contained the material for the nodule minerals. There is a close analogy to the miarolitic cavities of deep-seated igneous rocks, and to some types of litophys. The nature of the minerals, and the absence of any halogens (except the fluorine of the apatite) indicate that the compounds entering into the nodule minerals were in a state of solution in water. It is probable, that these solutions in most cases were above the critical temperature. Sometimes, however,

[8] The names *keratophyre* and *quartz-keratophyre* have also been used. The writer's reason for dropping them is the present uncertainty among petrographers regarding the exact meaning of these terms.

the connection between the nodule minerals and the normal groundmass of the rock is so intimate that this explanation seems doubtful. These "embryonal nodules" may represent spots where the rock magma, although in a liquid state, was rich in the volatile, nodule-forming constituents, that is, in a condition of "aqueo-igneous fusion."[9] The details in the evolution of the different kinds of nodules will not be understood until we have, by experimental work, obtained a better knowledge of the influence exercised by various gases in the magma under the conditions in question. Until then, we have to be content with some idea of the main features of the phenomenon.

The other rock type, the *quartz-porphyry,* is also sodic, but not so markedly as the syenite-porphyries. There may be some discussion as to the use of the name quartz-porphyry for these rocks, which generally do not reach higher in silica than to about 70 per cent. They are rather well distinguished from the syenite-porphyries, however, and the groundmass is that of a real quartz-porphyry, although the low silica content of the rock has not allowed any quartz phenocrysts to form. Dark minerals appear in small quantities only, magnetite generally predominating.

The Lapland *ores* are magnetites containing more or less apatite. Specular hematite of undoubtedly primary nature appears only in a very subordinate amount in the larger ore bodies; besides, it is the ore mineral of the inconsiderable Haukivaara deposits, which differ in many important respects from the other deposits.

The apatite content varies within wide limits, even within one single ore body. The phases richer in this mineral show many interesting textural features. Diopsidic augite is found as an important constituent in local phases of the Kiirunavaara ore body, and a light green hornblende is not uncommon. The latter is partly an alteration product of the augite (uralite) but probably in part primary. Titanite is rare and appears mostly in druses, or in the immediate wall rock of an ore body. The contacts of the ores are always sharply defined.

[9] The often observed increase of grain when nearing miarolitic cavities or other pockets exhibiting signs of the action of gaseous constituents may be cited as a probably analogous phenomenon.

Some of the larger deposits may be very briefly described as examples.[10] The giant *Kiirunavaara* ore body, with a mass of at least 750 million tons, forms a steeply inclined bed with syenite-porphyry, downward grading into syenite, for foot-wall, and quartz-porphyry for hanging-wall. The much smaller *Luossavaara* deposit appears on the same geological boundary after an interval of less than a mile. In both cases the contacts are well defined, but in several places there extend numerous apophyses from the ore body into the wall rock. Where these dikes and veins of magnetite are numerous, the mixture of rock and ore is called "ore breccia." Locally the porphyry at the contact is, to a width of one meter or somewhat more, transformed to a matted amphibole mass. These phenomena are known from the foot-wall contact only, the hanging-wall showing only slight changes near the ore.

The ore is magnetite, with a varying quantity of apatite. While the content of this mineral partly is nearly *nil*, there are other parts of the ore bodies where it is very high, the apatite often being segregated in a pure state as irregular "schlieren" and streaks. Within limited areas, the ore contains a considerable quantity of diopsidic augite, or of uralite. Titanite is rare: tourmaline has been found in a few places near the contacts with the wall rock. Microscopical crystals of zircon are found in most thin sections of apatite segregations.

At *Tuolluvaara* the ore deposit occurs in a porphyry almost identical in composition to the Kiirunavaara-Luossavaara hanging-wall rock (quartz-porphyry). The ore occurs in the form of dike-like, somewhat irregular bodies of workable size, and innumerable smaller dikes and veins down to almost microscopical stringers. The whole deposit may be described as an "ore breccia" analogous to that of Kiirunavaara, but of a much greater extension. The ore is magnetite with a lower average apatite content than the Kiirunavaara ore. Light green amphibole and white asbestos appear in some quantity. Small patches

[10] A more detailed description of the deposits around Kiruna will be found in a paper by the writer, this journal, Vol. V., 1910, p. 699 (author's abstract of the Kiruna monograph).

of calcite or quartz, with biotite and a little chalcopyrite and titanite appear here and there in the ore breccia. While insignificant in amount, they are of interest as probably representing the last "juice" of the ore-forming solutions.

At *Mertainen* the country rock is a syenite-porphyry with magnetite nodules. The ore is magnetite with little apatite and some amphibole and titanite. It occurs in the same way as at Tuolluvaara, that is, as dikes forming an "ore breccia." The largest bodies, however, are not dike-shaped as at Tuolluvaara, but extremely irregular.

Painirova is a small deposit in many respects similar to Mertainen. The apatite content is higher, however, and the crystals are larger than generally in the Lapland ores, reaching a length of several centimeters. These conspicuous apatite crystals often grow out from the walls of an ore body, or radiate from enclosed fragments of wall rock.

The *Ekströmsberg* deposits, which are of a considerable size (containing at least 50 million tons), form a series of beds with only narrow bands of quartz-porphyry between. The largest bed is magnetite, the others are partly magnetite, partly crystalline hematite.

The *Gellivare* group of deposits, which ranks next to Kiirunavaara in size, and also the important *Svappavaara* ore body, both occur in highly metamorphic rocks. While it is apparent that they are very closely related to those already enumerated, it has not as yet been possible to reconstruct the details of their original characters.

For the last twenty years, at least, it has been clear to all observers that the iron ores of Lapland must be genetically connected with the porphyries. Regarding the nature of this relation, however, and the conditions at the actual deposition of the ore minerals, opinions have widely differed.

The first working hypothesis that can claim consideration was formulated by Bäckström in 1898: "The iron ores occurring in association with effusive rocks should accordingly have obtained their material from below, during the last stage of the volcanic activity, in the form of compounds of iron, phosphorus

and titanium (chiefly chlorides and fluorides), emanating as gas or as superheated solutions. In the surface regions these have been decomposed by the water and the silicates they have been in contact with."[11] This pneumatolytic hypothesis is supported by De Launay.

Other authors regard the ores as magmatic bodies. Högbom (1898), when discussing the magnetite deposits in syenitic rocks in the Urals, points out their close resemblance to the Lapland ores, and gives good reasons for putting them together as a well defined genetic group of iron ores (low in titanium) as magmatic segregations in syenite rocks. This magmatic hypothesis has been taken up by Stutzer, and partly further developed.

Bäckström bases his view on the results of his examinations of the "nodules" of the ore-bearing porphyries, which show that minerals, among them magnetite, which normally are among the first to crystallize in the magma, here are the last components to form.

The advocates of the magmatic hypothesis find their most weighty arguments in the mineral composition of the ore, and in the relations between different ore varieties in one and the same ore body. They also point out the insignificance of the pneumatolytic metamorphism recorded in the ore-bearing rocks, which allows the inference that practically no halogen compounds have permeated them.

The present writer has been able to add something more to the evidence already brought forth by Högbom and by Stutzer. At the same time, however, it was plain that while Bäckström's hypothesis cannot longer be upheld in its original form, the observations on which it was founded cannot be neglected. The work resulted in the formulating of a working hypothesis which may be called a compromise between the rival views:

Most of the ore bodies, and particularly Kiirunavaara-Luossavaara, are regarded as products of magmatic crystallization. (With this expression is then understood crystallization in a liquid solution or melt at some temperature higher than the lowest

[11] While this view is first expressed in a paper of 1898, the quoted passage is from a later work ("Geol. Fören. Förh.," 1904, p. 182).

crystallization temperature of a granite pegmatite—about 550°.) The belief that the solution was in a liquid and not a gaseous state is chiefly founded on the textures of the deposits, and the relations between various ore varieties. The evidence of the supposed high temperature is found in the mineral composition, magnetite, apatite and some diopsidic augite. Minor constituents are zircon and biotite. Specular hematite fills fissures. It is a characteristic feature that the titanite, which in the ore-bearing rocks belongs to the last phase of magmatic crystallization, or to the period of pneumatolytic destruction, when found in the ores appears in vugs or in the skarn-like amphibole mass sometimes resulting from metamorphism of the wall rock immediately at the contact. The rare tourmaline behaves in the same way. It is apparent that ores of this composition are not formed from watery solutions at moderate temperatures; they must belong to the magmatic temperature range.

Some other smaller deposits point at a somewhat different origin. While the chief constituents are the same as in the large ore bodies—magnetite and apatite—and the textural features also indicate a very close relation, there appear in subordinate quantities certain constituents which are of great importance as "key minerals." Apatite dikes, which cut the quartz-porphyry of the Kiruna district, for instance, are very closely similar to phases of the Kiirunavaara ore body, but some of them contain considerable quantities of tourmaline, and a little albite and quartz. These minerals are often intergrown with the apatite. Zircon appears just as in the ores. Pyroxene is never found in these dikes.

These features seem to indicate that the relations of the apatite dikes to the porphyry are, in a way, analogous to those of a pegmatite to its mother rock—those of a "last juice of the magma." At the same time, the obvious resemblance to the Kiirunavaara ore leads us to believe that the only difference between the two has been that the apatite dike magma contained more volatile constituents and therefore probably crystallized at a somewhat lower temperature than the big ore body. There is every reason to believe that the large ore bodies bear a similar

relation to their mother magma as do the apatite dikes according to this interpretation. This "last-juice nature" is also shown by the other forms of smaller magnetite segregations in the porphyries, as a swarm of titanite-bearing magnetite veins on Luossavaara which, like the apatite dikes, are intimately associated with quartz-specularite veins, and also by the "nodules." Further, the microscopic examination of the ore-bearing rocks has shown it to be the rule that the crystallization of the magnetite takes place *after* that of the feldspar. This phenomenon is especially apparent in the curious magnetite-syenite-porphyry, in which the magnetite is squeezed in between the albite laths.

It is thus a characteristic feature of the ore-bearing rocks that the magnetite forms "the last juice." It may crystallize as a constituent of the rock, regularly distributed through its mass, or it may be separated out in some way or other, along with certain other constituents, particularly apatite, to form bodies of their own—small nodules, dikes or huge masses. This last juice necessarily contains the volatile constituents of the magma, which may, indeed, have been the ultimate cause of this appearance of the magnetite. In some cases, indeed, as in that of the nodules, it is probable that the magnetite crystallized from gaseous solutions. Some emanations traveled far, and deposited their iron content at lower temperatures. Thus a hydrothermal afteraction, after the eruption of the Kiruna quartz-porphyry, resulted in the lean quartzeous hematites of the Hauki complex. These ores are impregnations in silicified tuff rocks, and contain some tourmaline and orthite, but chiefly, besides the quartz, minerals characteristic of hydrothermal action near the surface: calcite, sericite, and a little barite.

While the proving of this nature of the magmatic differentiation which results in the Lapland ores, constitutes a step forward compared to the previously held views, the *cause* of this differentiation still remains to be found. There does not seem to be any possibility of explaining the phenomenon from the consideration of eutectic relations, in the way attempted by Vogt for magmatic differentiation in general.[12] The applicability of these views on

[12] J. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Vidensk. Selsk. Skr.*, Kristiania, 1908.

a case of ore differentiation in gabbro has recently been shown in a way that seems rather conclusive.[13] In the ore-bearing igneous rocks of Lapland, however, other factors must have been at work. The possibility of a limited miscibility of the spinellids in silicate magmas cannot be denied, but we have, as yet, no field or laboratory observations that corroborate such a view.[14] It is reasonable to suppose that the general chemical character of the magma has been a necessary condition for the kind of differentiation in question, but it has hardly been the only cause. Several features point to the existence of water in the ore magma, at least in some cases, and one is led to ascribe to this still somewhat mysterious agent some part in the differentiation process. The magmatic water is a deity that undoubtedly has been invoked more often than has been good for its credit, but we must not let the natural reaction carry us too far and lead to an underestimation of its possible importance.

When the "pegmatitic" relations of the Lapland ores to their mother magma became clear, it was at the same time apparent that these magmatic iron ores are formed through a process radically different from the one that gives birth to the titaniferous ores. The latter are, as is well known, concentrations of the *first* crystallizing components, while the Lapland ores represent that part of the magma which is the last to crystallize.

The existence of several types of such late-magmatic ores, as one might call them, is proved, but they are not common. Late magmatic ores are included in Leith's "pegmatite type" of iron ores,[15] and in Bergeat's "perimagmatic group."[16] Both these terms which, so far as iron ores are concerned, may be regarded as synonyms, have a very wide scope.

Speaking of the ores as igneous rocks, we must call some deposits, for instance Tuolluvaara and Painirova, intrusive

[13] S. Foslie, "The Ramsöy Deposits of Titaniferous Iron Ore," *Norges Geol. Unders. Aarsbok*, 1913, IV.

[14] Compare, however, A. Harker, "The Natural History of Igneous Rocks," p. 200.

[15] C. K. Leith, "Iron Ores of Canada," ECON. GEOL., Vol. III., 1908, p. 276.

[16] A. Bergeat, "Epigenetische Erzlagerstätten und Eruptivgesteine," *Fortschritte der Mineralogie*, etc., Vol. II., pp. 9–23.

bodies. The ore beds of Ekströmsberg, on the other hand, appear to belong to a series of surface flows. For Kiirunavaara-Luossavaara, no decisive proofs in either direction have been found. Many geologists, including the writer, find the presence of ore fragments in the hanging-wall porphyry a very strong argument for the view that ore bodies have been formed at the surface. Others, among them Stutzer, believe them to be intrusives. For this view, a number of proofs are brought forth, among which none can be accepted as decisive, but which together compel consideration.

Several other iron ore deposits are often classed with those of Lapland as belonging to the same genetical group: Grängesberg in Central Sweden, Solberg and Lyngrot in Southern Norway, the Mineville group in the Adirondacks, Iron Mountain in Missouri, the Blagodat type of thé eastern Ural Mountains, Cerro de Mercado at Durango in Mexico. Of these deposits, Grängesberg, Solberg-Lyngrot, and Mineville are apatite-bearing magnetites in more or less gneissic rocks, and resemble Gellivare, the most highly metamorphic representative of the Lapland ores. It is obvious that part of the present analogies may be due to similarity in metamorphism rather than in original nature.

The analogy between the "Old bed" at Mineville and the Gellivare ore bodies was pointed out by Sjögren in 1891. At that time, opinions differed widely with regard to the origin of these deposits. Since then, observers in both districts have independently arrived at the conclusion that the ore-bearing rocks are igneous, and the ores themselves magmatic segregations. Recently, Newland has emphasized the similarities that make the "21" mine at Mineville almost an exact counterpart of some of the Gellivare open cuts. From my own visit to Mineville, I have a strong impression of these analogies. There are, however, some important differences. The ore-bearing rocks of Mineville are undoubtedly deep-seated intrusives, but those of Gellivare probably intrusions at shallow depths.[17] The chemical compo-

[17] The exact mode of occurrence of the Gellivare rocks cannot be determined in their present recrystallized stage. They cannot be abyssal, however, and may even possibly be extrusives, like the Kiruna porphyries.

sition of the syenites seems to be very much the same in both districts, but the close association with anorthosites is without a parallel in Lapland, where the ore-bearing magma shows other chemical relations. Yet it seems very probable that the Mineville deposits represent a deeper—perhaps one could say earlier—stage of the same differentiation process that has given rise to the Lapland ores.

In the case of the Ural ores, or the deposits of Iron Mountain or Cerro de Mercado, it is clear that analogies with the least metamorphosed Lapland ores can be safely accepted as evidence of similarity in origin. Högbom, in 1898, concluded that there were no other ore deposits known which are more closely related to the Lapland ores than are those of Ural. Since then, prominent investigators have found reason to regard part of these Russian deposits in question as products of igneous metamorphism. Even if this should be right, however, it does not preclude the supposed relation to the Lapland ores. If the views of the differentiation process given here are right, one may expect to find, in close association with deposits of a magmatic nature, others formed at lower temperatures or through the action of gaseous compounds. In fact, as will be shown later on, one finds in America a somewhat similar example. It must also be remembered that several important analogies have become known since Högbom wrote his paper, for instance the existence of the curious magnetite-syenite-porphyries also in Lapland.

To judge from available descriptions, the Cerro de Mercado, at the city of Durango, Mexico, certainly belongs to the ore type now under discussion. It seems, however, to be the only representative of the type described from Mexico.

Although Iron Mountain and related deposits in southeastern Missouri are among those sometimes classed with the Lapland ores, it has hardly been known that they share with eastern Ural the position of being the nearest relative to the metallo-genetic province of northern Lapland. Professor J. F. Kemp was the first to call my attention to this district. Later, I became acquainted with the important work recently carried out by Mr. G.

W. Crane, for the Missouri Bureau of Geology and Mines.[18] I was able to pay a brief visit to the chief mines, Iron Mountain and Pilot Knob.

The ore-bearing porphyries are on the whole rather similar to those of Lapland. One detail that I have not seen mentioned in the literature at my disposal is the local occurrence of "nodules" of specular hematite, in every respect similar to the magnetite nodules of the syenite-porphyries of Kiirunavaara and Mertainen. The nodule-bearing rock is probably of very local occurrence. I observed it only as a few big blocks at the largest open cut on Iron Mountain.

The mode of occurrence of the primary or vein ore at Iron Mountain is almost precisely the same as at Tuolluvaara in Lapland: in both cases there appear some larger, dike-shaped masses, and a system of smaller dikes and veins, forming what is in Lapland known as an "ore breccia." No deposit in Lapland so closely approaches Tuolluvaara in these respects as does Iron Mountain. The composition of the ore differs from that of most Lapland ore bodies by the fact that the iron appears as specular hematite and not as magnetite. This difference, in itself of little importance, is further reduced by the possibility that the hematite may be martitic. The quartz, the last mineral to form in the Iron Mountain ore, does not appear in more than insignificant amounts at Tuolluvaara. Otherwise, the composition is the same, with apatite as the chief barren mineral, and some tremolite. The texture of the ore, however, is different. At Iron Mountain the apatite appears in prismatic crystals which grow out from the walls of the narrow ore veins, or radiate from inclusions of porphyry in the ore mass. While this texture is not observed at Tuolluvaara, it is, as already stated, very characteristic of another deposit in Lapland, Painirova.

The sub-Cambrian talus or "conglomerate ore" of Iron Mountain very much resembles the "conglomerate with hematite pebbles" which occurs in the sedimentary Hauki complex at Kiruna, somewhat higher up in the stratigraphical sequence than the ore-bearing porphyries.

[18] G. W. Crane, "The Iron Ores of Missouri" (Missouri Bur. Geol. and Mines, 2d ser., Vol. X.).

While Iron Mountain thus combines features of Tuolluvaara and Painirova, Pilot Knob forms a striking analogy to Haukivaara. At both places there is a succession of rocks of probably agglomeratic and tuffogeneous nature, strongly altered through hydrothermal activity, silicified or changed to sericite schists, and impregnated with hematite. The "ferruginous breccia" of Pilot Knob is almost identical with a common form of the leaner ore at Haukivaara. The occurrence of some barite is also a characteristic feature at both places.

Crane summarizes his views regarding the origin of the ores as follows:[19] "The ores, in general, are regarded as having been deposited from hot, iron-bearing solutions as an after effect of the porphyry extrusion, the solutions coming from the porphyry itself or from a source common to that of the porphyry. That at Shepherd Mountain is very largely a filling of stretch fissures due to the cooling and consolidation of the porphyry; that at Iron Mountain is in part fissure filling, but more largely a replacement of the porphyry, while that interstratified with porphyry breccia, as at Pilot Knob, Cedar Hill, and Russell Mountain, represents the more or less complete replacement and infiltration of stratified tufaceous beds by iron oxide."

Judging from my own hasty observations, I should believe that Mr. Crane has to some extent exaggerated the importance of the replacement process in the forming of the Iron Mountain ore. While proofs of replacement in small details are abundant, the dikes and veins, particularly the larger ones, have all appearance of being fissure fillings. In Lapland we have few examples of a replacement of wall rock by ore, but some cases where amphibole appears in this way. The same may possibly be the case at Iron Mountain. This unimportant detail excepted, Mr. Crane's results are absolutely the same as I have reached concerning the nearest Swedish relatives of these deposits. It is true that Mr. Crane speaks of the iron-bearing solutions only as *hot*, while I believe most of the Lapland ores to have been formed at magmatic temperatures, but this is of little consequence. For Iron Mountain, for instance, no direct proof of the temperature

[19] *Op. cit.*, p. 139.

can be given, because of the absence of "key minerals"; all we can conclude is that the temperature has been higher than in most mineral veins, and at least approached the magmatic range. Whether it has actually been above the 550° limit, or a little below, does not constitute any important difference.

The recurrence of the types Tuolluvaara-Painirova and Haukivaara in Missouri, there represented by Iron Mountain, Shepherd Mountain, and Pilot Knob, respectively, strengthens the view that these two types of deposits represent different phases of one kind of differentiation, in a wide sense of the word. The data we can get out of the Missouri district thus uphold the working hypothesis proposed for the Lapland ores.

Certain other American iron ore deposits appear to be rather closely related to those of Missouri. The Barth deposit at Palisade, Nev., recently described by Mr. J. Claude Jones,[20] shows similar relations to the wall rock as does the ore of Iron Mountain. The ore is magnetite with a considerable percentage of apatite. The latter is often gathered spotwise, as is so often the case in the Lapland ores. It is remarkable that the ore occurs in a femic andesite, but one may ask whether, in this and similar cases, the actual wall rock always is also the one genetically most closely connected with the ore. At Palisade, rhyolitic rocks are also reported, but they are not ore-bearing.

The dikes and veins of magnetite at Iron Springs, Utah, are rich in apatite and show the same appearance of this mineral as the Iron Mountain ore.[21] It may be pointed out as an interesting detail, that the Iron Springs ore sometimes (specimens in the Columbia University collections) shows "columnar jointing," with columns about one inch in diameter. Identically the same phenomenon is shown by the Kiirunavaara ore, but only within very small areas.[22]

The appearance, at Iron Springs, of magnetite dikes and con-

[20] J. Claude Jones, "The Barth Iron Ore Deposit," ECON. GEOL., Vol. VIII., 1913, p. 247.

[21] Compare descriptions by C. K. Leith and E. C. Harder, U. S. Geol. Survey, Bull., 338.

[22] Per Geijer, "Igneous Rocks and Iron Ores of Kiirunavaara, etc," pp. 86–87.

tact deposits of the same mineral in the closest connection is a remarkable feature that gives us some hints at the probable explanation of the mysterious points in the geology of the Ural magnetites.

The nelsonite of Virginia is probably an analogue to the other titaniferous iron ores, and not to the group we have discussed here. It is a striking feature, however, that its apatite is of the fluorine-bearing variety, whereas apatite associated with gabbro generally contains more chlorine than fluorine.

A catalogue entitled "Maps and Memoirs on Swedish Geology" was published by the Geological Survey of Sweden in 1910. In the section "Ore Deposits" (compiled by Prof. H. Sjögren) will be found discussed all the papers relating to the Swedish deposits published before June, 1910. Some papers dealing mainly with other sides of pre-Cambrian geology, and in the catalogue listed under the heading "Pre-Cambrian Systems" are also of a great interest to the students of ore deposits. "Pre-Cambrian Geology of Sweden," by A. G. Högbom (Bull. Geol. Inst. Upsala, Vol. X., 1910, pp. 1–80), is a review intended to serve foreign geologists as an introduction to the problems of the Swedish pre-Cambrian. "Archæan Geology of the Coast-regions of Stockholm," by P. J. Holmquist,[23] contains a description of the ore-bearing formation of Utö, with large-scale maps.

The following list contains papers published after the catalogue, and some papers dealing with the quartz-banded ores of northern Norway.

PER GEIJER. Ein Vorkommen von turmalinführendem Eisenerz in Diabas (*Geol. Fören. Förh.*, Vol. 33, 1911, pp. 21–31).

Contributions to the Geology of the Sydvaranger Iron Ores (*Geol. Fören. Förh.*, Vol. 33, 1911, pp. 312–343).

Studies on the Geology of the Iron Ores of Lapland (*Geol. Fören. Förhandl.*, Vol. 34, 1912, pp. 727–789).

P. J. HOLMQUIST. Texture and Metamorphism of the Iron Ores (Swedish,

[23] *Geol. Föhren. Förh.*, Vol. 32, 1910, pp. 789–913; also as guide No. 15, 11th Internat. Geol. Congress.

with a summary in German. *Geol. Fören. Förh.*, Vol. 35, 1913, pp. 233–272).

NILS SUNDIUS. Pebbles of Magnetite-Syenite-Porphyry in the Kurravaara Conglomerate (*Geol. Fören. Förh.*, Vol. 34, 1912, pp. 703–726).

J. H. L. VOGT. Über magmatische Ausscheidungen von Eisenerz in Granit (*Zeitschr. f. prakt. Geologie*, XV., 1907, pp. 86–89).

Norges jernmalmsforekomster (Iron Ores of Norway). *Norges Geol. Unders.*, No. 51. Kristiania, 1910.

J. H. L. VOGT, WITH F. BEYSCHLAG AND P. KRUSCH. Die Lagerstätten der nutzbaren Mineralien und Gesteine (Sydvaranger, etc., in Vol. I., 2, pp. 259–266).

SULPHIDE-BEARING ROCKS FROM LITCHFIELD, CONN.

ERNEST HOWE.

INTRODUCTION.

Certain gabbros and related rocks in western Connecticut have been described by Hobbs[1] and compared with the "Cortlandt Series" of the Hudson River studied by Dana, Williams, and Kemp. The rocks are found in the neighborhood of Prospect Hill, about five miles west of Litchfield.

In years past a few nickel-bearing sulphide deposits were explored by shallow shafts near Prospect Hill, but according to local accounts active "mining" ceased some fifty years ago when it became evident that the ore was of too low grade and in too small quantities to warrant further operations. Although economically of no value, the "ores" are of some interest on account of their association with gabbros and related rocks which have suffered neither dynamic nor hydro-thermal metamorphism.

The various rocks have been well described by Hobbs who shows that they have strong family resemblances to those of the type locality of the "Cortlandt Series" at Peekskill on the Hudson River. He recognizes gabbros, norites, peridotites, pyroxenites, diorites, and granodiorites, and in many the presence of pyrrhotite and chalcopyrite is noted. He believes "that the generally rare gabbro, norite, peridotite, and pyroxenite types which most nearly correspond to the original 'Cortlandt Series,' belong to a single magma which has here been intruded along the mutual borders of areas of granite, granodiorite, and diorite, which may themselves have mingled to some extent; and that it has itself been later intruded by a fine-grained diorite. The extreme mag-

[1] Hobbs, W. H., "On Two New Occurrences of the 'Cortlandt Series' of Rocks within the State of Connecticut," Festschrift v. H. Rosenbusch, pp. 25-48, Stuttgart, 1906.

matic differentiation of this gabbroitic magma has been locally increased through the fusion with it of granite and granodiorite."[2]

During a recent visit to the Prospect Hill locality I collected specimens from three of the old mines with the object of studying the sulphides and their relation to the silicates. Unfortunately there are few outcrops near the mines and the shafts have caved or are filled with water, so that it is only possible to say that the ore bodies appear to have consisted merely of rock more richly impregnated with sulphides than the country rock near by; there is at present no means of finding out whether the ore grades into country rock or is bounded by sharp contacts. Three localities were visited: the Grannis mine west of Prospect Hill; Buck's nickel mine southeast of the hill; and the Connecticut Nickel Company's mine, one mile south of the summit of the hill. At the Grannis mine there is a water-filled shaft and a short tunnel evidently started as a cross-cut but abandoned before reaching ore. The Buck mine consists of four shafts within a hundred feet of each other and at the Connecticut Company's mine there is one shaft.

DESCRIPTION OF THE ROCKS.

The rocks collected at these localities belong to one or another of the types recognized by Hobbs, and differ from each other mainly in the relative abundance of the soda-lime feldspars and in the character of the ferromagnesian minerals. Some are characterized by an abundance of rhombic pyroxene, others contain notable amounts of olivine, while a few are rich in hornblende. Pyrrhotite and chalcopyrite are present in all.

For purposes of discussion three general types of rocks may be recognized: norites, pyroxenites, and peridotites. This distinction is purely arbitrary, however, as many intermediate rocks occur which make up an unbroken series grading from one extreme to the other.

The peridotites were found at the Buck mine. They are dark brown rocks of medium coarse grain (0.5–2.5 mm.), contain many large (25 mm.) pyroxenes, and are plentifully sprinkled

[2] *Op. cit.*, p. 48.

with specks and small masses of metallic sulphides. The rocks are made up largely of olivine and monoclinic pyroxene with a little rhombic pyroxene, pale yellow-green or colorless hornblende, biotite, and considerable magnetite, pyrrhotite, and chalcopyrite, with apatite and a little bright green spinel, possibly pleonaste, as accessories. Plagioclase is only sparingly present and in none of the slides is it well enough developed to afford accurate determinations. These rocks are remarkably fresh and, with the possible exception of a little calcite, which may be an original mineral, there is nothing to indicate that they have undergone post-magmatic alteration.

This same freshness is also characteristic of the rocks that have been classed as norites associated with the less feldspathic rocks at the Buck mine, and which are the prevailing rocks at the Grannis mine. The Grannis rock is a nearly typical norite. It is brownish-gray, medium to fine grain (0.5–1.0 mm.) and consists roughly, in volume, of nearly equal amounts of feldspar and pyroxene (which together make up about 90 per cent. of the rock), biotite, hornblende, and about one per cent. of miscellaneous accessories of which pyrrhotite and chalcopyrite make up the greater part, together with magnetite, rutile, and a very little titanite. The feldspar is bytownite, and the pyroxene enstatite or bronzite with a little diallage often intergrown with it; hornblende is brown to pale greenish-yellow. In one slide a very little quartz is present, and plagioclase, less basic than in the other rocks, is a rare constituent. The relative quantities of pyroxene and hornblende are difficult to determine because of the frequent intergrowth of these minerals as described in a later paragraph.

Between these fairly typical norites and the peridotites examples of many intermediate rocks are found, as well as more extreme types, such as pyroxenites, some of which are rich in poikilitic brown-green hornblende. In all of these rocks the metallic sulphides, pyrrhotite and chalcopyrite, are more or less abundant.

Several features of the Prospect Hill rocks are noteworthy. Most striking, perhaps, is the presence of the sulphides, while the abundance of hornblende and biotite, often intimately associated with the sulphides, is rather unusual in rocks of this gen-

eral type. The great freshness of the rocks is especially noteworthy; they have not been dynamically metamorphosed, and all of the silicates appear to have had a magmatic origin. A more detailed study leads to the conclusion that the sulphides also are magmatic.

CHARACTERISTICS OF THE HORNBLENDE.

The presence of hornblende in pyroxenic rocks, especially as borders or reaction rims about pyroxene, is often an indication that the rocks have undergone post-magmatic alteration. Such hornblende is usually of the uralitic variety, but it may sometimes be massive. It is important, therefore, to determine the character of the hornblende in the Prospect Hill rocks, since if it were secondary there might be reason to doubt the original character of the sulphides.

Many of the norites show with special clearness the nature of the hornblende and its relations to the pyroxenes. It is most noticeable as interstitial masses one half to one millimeter in diameter; poikilitic crystals with pyroxene inclusions are also common. Hornblende is also found in the form of bands or rims at the ends of or completely surrounding pyroxene crystals (Fig. 45.) These rims extinguish as parts of single crystals and are not fibrous aggregates. There are instances where the development of hornblende rims has been followed by a later growth of pyroxene and this in turn followed by more hornblende. Some pyroxenes have been partially resorbed and later surrounded by hornblende.

Pyroxene seems clearly in some cases to have been replaced by hornblende, the process taking place along cleavage cracks. Instances of what appears to be a more complete replacement are best shown in basal sections where cores of pyroxene are surrounded by hornblende oriented crystallographically with the pyroxene and preserving perfectly the pyroxene outline (Fig. 46). Distinct veinlets of brown-green hornblende, 0.1–0.2 mm. wide, with which are associated biotite, plagioclase and sulphides, are shown in one slide, and it is evident that all of these minerals are younger than the pyroxenes, across which they cut. The appearance of the hornblende, however, is precisely that of the large in-

terstitial or poikilitic masses. This is well shown where one of the veinlets cuts a large mass of hornblende. In ordinary light the hornblendes of the two modes of occurrence blend completely and appear to make up one individual from which vein-like branches extend outward into areas of pyroxene. With crossed nicols, however, the finely granular character of the veinlet shows

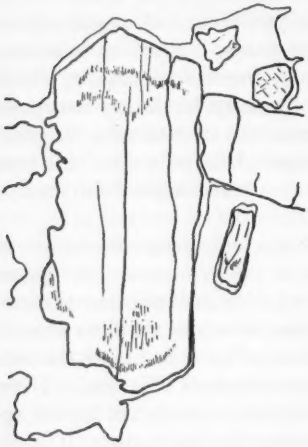

FIG. 45.

FIG. 46.

FIG. 45. Pyroxenes surrounded by rims of hornblende. × 37.
FIG. 46. Basal section of pyroxene partly replaced by hornblende. × 110.

it to be younger than the large mass of hornblende. Hornblende predominates in these veinlets, making up about 80 per cent. of the whole, the other minerals being sulphides 10 per cent., biotite 8 per cent., and plagioclase 2 per cent.

The hornblende present in the olivine-rich rocks, except for its color, which is a brighter green, differs in no essential from that found in the norites.

BIOTITE.

Biotite is a common associate of the hornblende, and its modes of occurrence are essentially the same. It is usually found in

0.5 to 1.0 mm. patches of irregular outline often enclosing sulphides and magnetite. Like hornblende it is also present in veinlets and has developed along cracks in pyroxene; it has not been found in the form of rims or borders to pyroxene, however.

PYRRHOTITE AND CHALCOPYRITE.

The sulphides are most frequently associated with hornblende and biotite, and are often included in these silicates. Inclusions of euhedral or subhedral magnetite are common. With respect to pyroxene and olivine the sulphides are interstitial or moulded on the subhedral crystals. Sometimes the surfaces of pyroxene, with which the sulphides are in contact, are rounded or embayed as

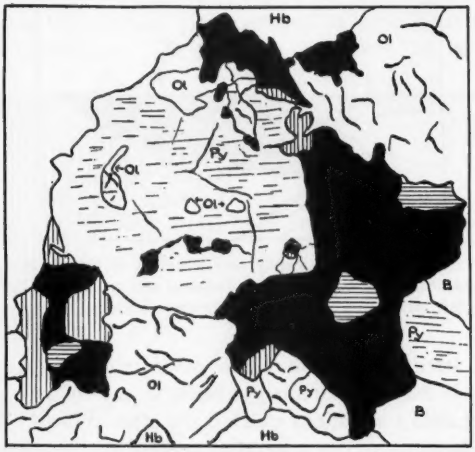

FIG. 47. Silicates, magnetite and sulphides. × 24. Black: pyrrhotite; horizontal shading: chalcopyrite; vertical shading: magnetite; Py: pyroxene; Ol: olivine; B: biotite; Hb: hornblende.

if the silicates had suffered partial resorption before the sulphides appeared or had been replaced by the sulphides. Rarely small patches or grains are found in the interior of pyroxenes; they are different in form and size from the sulphides included in the horn-

blende and biotite, however, and are always in contact with cracks or fractures in the pyroxene, and almost always associated with them is hornblende or biotite; these seem clearly to be interpreted as having replaced pyroxene. These same relations hold true in the case of hornblende and biotite. Some of these features are shown in Figs. 47 and 48.

A sharp line can not be drawn between silicates that have suffered partial magmatic resorption to be later more or less enclosed by sulphides, and those that have been replaced by sulphides. Partial magmatic resorption may leave a mineral grain with a surface

FIG. 48. Euhedral pyroxene nearly surrounded by sulphides; other silicates embayed and penetrated by sulphides. Polished section, vertical illumination. ×24. Shaded: pyrrhotite; dotted: chalcopyrite; white: silicates.

of great irregularity upon which other minerals may be deposited. It may be extremely difficult to say in individual instances of such associations which is the older mineral. Metasomatic replacement of one mineral by another may result in a relationship of the two minerals that appears precisely the same as that brought about by magmatic resorption, but replacement may also develop relationships that can in no way be explained by the resorption of one mineral and the later deposition in its place by another. To this last class belong the irregular patches of sulphide near cracks or cleavage lines in pyroxenes. Biotite is often penetrated by long, narrow tongues of sulphide, or the two are

intergrown in such an intricate manner that the sulphide can be accounted for only on the assumption that it has replaced biotite.

In no case has any pyrrhotite or chalcopyrite been observed with crystal form, nor, with one exception, have they been found possessing the crystal forms of other minerals as the result of replacement. The exception is magnetite, euhedral inclusions of which in hornblende have been replaced by pyrrhotite. Sulphides are intimately associated with hornblende, biotite and plagioclase in the veinlets that have been described.

PENTLANDITE.

The nickel-bearing mineral pentlandite has thus far not been mentioned because it is practically impossible to distinguish it from pyrrhotite in thin sections, which are best to show the relation of sulphides to silicates. The sulphides themselves can be studied

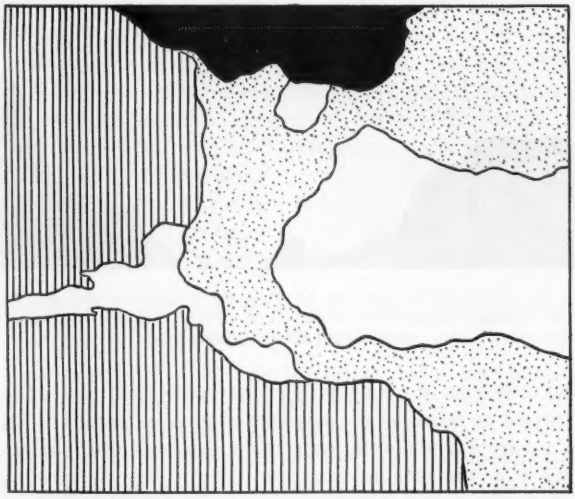

FIG. 49. Pyrrhotite "intruded" or replaced by pentlandite which is in turn cut by chalcopyrite. Polished section, vertical illumination. ×63. Black: silicates; vertical shading: pyrrhotite; white: pentlandite; dotted: chalcopyrite.

better under the microscope in polished sections with vertical illumination, and examined in this way pentlandite is easily recognized. Pyrrhotite, the most abundant sulphide, is frequently cut or traversed by what may best be described as intrusive masses of pentlandite, and the pentlandite is in turn cut by chalcopyrite. These features are shown in Figs. 49 and 50. There are also many instances where small rounded grains of chalcopyrite appear as simple inclusions in pyrrhotite, or where one end of a mass of sulphides is composed of pyrrhotite and the other of chalcopyrite, the two minerals being present in nearly equal amounts. The ap-

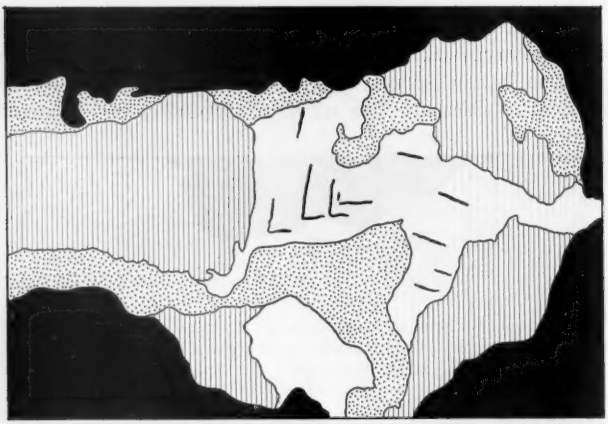

FIG. 50. Chalcopyrite intruding or replacing pentlandite and pyrrhotite. Polished section, vertical illumination. × 90. Black: silicates; vertical shading: pyrrhotite; white: pentlandite; dotted: chalcopyrite.

parent inclusions of chalcopyrite in pyrrhotite may, of course, be interpreted as intrusive tongues viewed in cross section. These relations are essentially the same as those found to be true of the sulphides in the ores at Sudbury, Ontario, by Campbell and Knight.[3] There is nothing to suggest in the Litchfield rocks that

[3] Campbell, William, and Knight, C. W., "On the Microstructure of Nickeliferous Pyrrhotites," ECON. GEOL., II., 350–366, 1907.

the earlier sulphides were fractured and that the introduction of the later sulphides was thus directed and facilitated, the explanation offered by Campbell and Knight to account for the relations of the pyrrhotite, pentlandite, and chalcopyrite in the Sudbury rocks. It can not be denied, however, that pentlandite and chalcopyrite have every appearance of being younger than pyrrhotite and that they look as if they had replaced the older sulphide, yet in relation to the silicates they differ in no way from one another. That is, an area composed of the three sulphides is as clearly interstitial with respect to the surrounding silicates as are masses of pyrrhotite alone. Since the silicates show no evidence of alteration, such as would be expected had the sulphides been introduced by metasomatic processes after the complete consolidation of the rocks, it must be assumed that, not only was the association of sulphides and silicates brought about at the time that the magma was crystallizing, but that the relations of the sulphides to one another were also determined during the magmatic period.

In describing the sulphides in certain of the Sudbury rocks I suggested that these same relations might have been brought about "by the nearly simultaneous cooling of the different sulphides that had previously separated as distinct mineral compounds, nonmiscible, though still molten."[4] Here again it is perhaps impossible to distinguish between the processes of resorption and replacement if both are supposed to have taken place under magmatic conditions. These questions are taken up again in discussing the crystallization of the magmas.

SUMMARY OF MICROSCOPIC EVIDENCE THAT THE SULPHIDES ARE OF MAGMATIC ORIGIN.

There is nothing to indicate that the sulphides were introduced through metasomatic processes after the solidification of the rocks. There can be no reason to doubt the magmatic origin of the hornblende, even in the more extreme cases where hornblende has replaced pyroxene, and none of the silicates shows the slightest evidence of post-magmatic alteration due to hydrothermal or

[4] Howe, E., "Petrographical Notes on the Sudbury Nickel Deposits," ECON. GEOL., IX., 505–522, 1914.

dynamic agencies, while the relation of the larger sulphide masses to the silicates is typically interstitial and as characteristically so as quartz in more siliceous rocks. Disregarding for the moment the much less conspicuous occurrences of sulphides and hornblende as probable replacements along cleavage cracks in pyroxene, and in veinlets associated with biotite and plagioclase, it may be assumed without further discussion that pyrrhotite, pentlandite, and chalcopyrite are of magmatic origin.

CRYSTALLIZATION OF THE MAGMAS.

A study of the progress of crystallization of the magmas represented by the rocks under discussion, notwithstanding the possibility of certain events being unrecorded in the final products, brings out a number of facts that seem to have a direct bearing on the origin of the sulphides. Whatever minerals may once have appeared only to be resorbed, it is very evident that olivine, apatite, magnetite and the pyroxenes were the first minerals to crystallize in the period that is now on record. Distinctly later than this group of minerals are hornblende, biotite, plagioclase, and the sulphides. Their time of maximum development followed a period during which olivine, magnetite, and the pyroxenes suffered greater or less resorption, yet under conditions which permitted pyroxene to continue to separate and sometimes to alternate with hornblende in its crystallization. The minerals of the second group are always younger than the olivine, but the relation of pyroxene to hornblende and the sulphides is more complex. There are many instances of repeated growths of hornblende on pyroxene followed by periods of pyroxene crystallization alone. Poikilitic masses of hornblende with pyroxene inclusions, both minerals having the same crystallographic and similar optical orientation, are occasionally found; they look as if larger pyroxenes had been replaced by hornblende but in the process the subhedral outline of the pyroxene had been lost. There are, however, a number of instances in one slide where brown hornblende has clearly replaced pyroxene, best shown in basal sections in which the pyroxene outline is preserved and which are composed of hornblende

with good prismatic cleavage surrounding cores of pyroxene (Fig. 46).

Plagioclase is always younger than pyroxene but its relation to hornblende is less clearly defined. In cases where pyroxene, hornblende and plagioclase are in close association, hornblende is seen to have begun to crystallize before plagioclase, but it also continued to form after the plagioclase made its appearance, as shown by its inclusion of feldspar grains. Hornblende is certainly younger than the plagioclase in one case where a veinlet of brown hornblende, biotite, and plagioclose cuts older plogioclase crystals.

The absence of sulphides from intimate association with minerals of the earlier generation suggests, but does not necessarily prove, that they first made their appearance after the crystallization of olivine and pyroxene was well under way or completed. The rare occurrence of euhedral or subhedral magnetite grains, except as inclusions in the sulphides, is noteworthy. The magnetite is undoubtedly older than the sulphides and must be regarded as belonging to the earlier period of crystallization, along with olivine and pyroxene. The magnetite grains are frequently corroded or partially resorbed when included in the sulphide masses, and a few very perfect pseudomorphs of pyrrhotite after magnetite have been found as inclusions in large masses of hornblende. This suggests that after the crystallization of magnetite the equilibria of the solid and liquid phases of the magma were disturbed and magnetite began to dissolve, but before solution was in all cases complete the corroded grains were surrounded, and perhaps protected, by a layer of sulphide. It is possible that the resorption of the magnetite was in some way related to the nearly simultaneous appearance of the sulphides. Among other things it shows pretty conclusively that the sulphides began to appear at an early stage of the crystallization of the silicates, though they were not necessarily among the first to seperate. From that time on to the final consolidation of the rocks the sulphides seem to have continued to separate, being found as inclusions in hornblende, biotite, and plagioclase, and as having replaced these minerals;

they are also present in hornblende-biotite-plagioclase veinlets that are younger than all the other silicates.

THEORETICAL DISCUSSION OF THE MAGMATIC ORIGIN OF THE SULPHIDES.

In reviewing the various features peculiar to these rocks that have been described, one is impressed by the very evident change that occurred in the crystallization of the magmas, resulting in the partial solution of some of the earlier formed silicates and the separation of a new group of minerals. From the microscopic evidence one is inclined to associate the sulphides with the later minerals. Was the partial resorption of the earlier silicates and the character of the later minerals due to some influence outside of the magma and perhaps connected with the appearance of the sulphides, or, was the resorption of the olivine, pyroxene, and magnetite brought about only by natural changes and readjustments in equilibrium between the different phases of the cooling magma, and were all of the later minerals present in a liquid phase at that time? A microscopic study alone fails to answer these questions satisfactorily, but if the evidence is examined with due regard to the general principles of physical chemistry as applied to cooling magmas, it seems to favor the last hypothesis.

It is entirely possible that some external cause, such as change of pressure or temperature, might be held responsible for certain of the peculiarities that have been noted, while the introduction, through the agency of mineralizers, of the sulphides as new components of the magma at some time after crystallization had begun might, not unreasonably, be regarded as a contributing cause of the equilibrium changes indicated by the resorption of the earlier silicates. The difficulty, however, of accounting for the abundance and even distribution of the sulphides throughout the partially crystallized magma, if introduced in some such way as suggested, offers a serious objection to the acceptance of this idea.

On the other hand, the various events that took place in the crystallization of the magmas, as shown by microscopical study,

are in no way inconsistent with the theory that all of the minerals now present were represented in the original components of the magmas, and that the phenomena of resorption and replacement that have been noted merely represent readjustments in equilibria between solid and liquid phases during the gradual cooling and crystallization of the magmas. If this point of view be accepted it will be well to consider in some further detail the relation of the sulphides to the other constituents.

In such complex systems as those of the magmas under consideration separation and resorption of certain minerals during the early stages of cooling are not only theoretically possible but probable. Bowen has shown experimentally that, in the case of artificial melts of the system diopside-fosterite-silica "from which olivine is the first mineral to crystallize, the olivine is at a later stage either partly or completely redissolved, giving pyroxene by reaction with the liquid. This resorption takes place in the normal course of crystallization on cooling and is the necessary result of equilibrium between the phases."[5] In the case of the silicates themselves, therefore, it would appear to be unnecessary to call upon any outside influence, other than the gradual lowering of the temperature, to account for the phenomena of resorption.

Information concerning the relative solubilities of molten sulphides and silicates in one another is derived from observations at various temperatures but under conditions which preclude the presence of gases or mineralizers in the melts. Under such conditions liquid sulphides and silicates are practically non-miscible. It is not improbable, however, that the solubility of sulphides in silicates might be notably increased if gases or other mineralizers were held in solution in the magmas at suitable pressures.

The larger masses of sulphides in the Litchfield rocks may well have separated from solution at an early stage of the cooling of the magmas whether mineralizers were present or not, but it is quite possible, even if mineralizers were absent, that they did not begin to separate until after the first silicates had started to crystallize. Had there been a considerable interval between the

[5] Bowen, N. L., "The Ternary System: Diopside-Fosterite-Silica," *Am. Jour. Sci.*, vol. 38, p. 256, 1914.

time when the sulphides separated and when the first silicates began to crystallize, the sulphides must have settled to the lowest portion of the magma, the remaining liquid crystallizing as a sulphide-free rock. If, however, the silicates began to crystallize before the sulphides started to separate, or even if they separated simultaneously, the segregation of the sulphides by gravity would have been greatly hindered if not prevented, and sulphides and silicates would appear together in the final product. In the case of the Litchfield rocks, therefore, there seem to be good reasons for concluding that the crystallization of some of the silicates began before, or, at least, contemporaneously with, the separation of the sulphides. The melting points of the sulphides being lower than those of any of the associated silicates, the pyrrhotite, pentlandite and chalcopyrite presumably would remain liquid after all the silicates had crystallized. Consequently, although they might have been among the earliest minerals to separate, they would not assume crystal form but would appear in the end as interstitial masses, apparently younger than any of the silicates.

There is nothing in the evidence derived from a microscopic study of the Litchfield rocks opposed to the idea that the larger masses of sulphides may have had such an origin as that suggested. There seem to be good reasons for believing, however, that small quantities of sulphides continued to separate from solution until nearly the close of the period of crystallization of the magmas, and that pyrrhotite may even have suffered resorption. Such conditions are in no way inconsistent with the physico-chemical principles that apply to cooling magmas, except that they seem to indicate a greater degree of solubility of the sulphides in a silicate magma than one would be led to expect from the practical immiscibility of sulphides and silicates, in the absence of mineralizers, under atmospheric conditions. If the presence of mineralizers is granted, there can be no objection, from the point of view of physical chemistry, to the conclusion that the sulphides in all their occurrences—as interstitial masses, as replacements of silicates, and as associates of hornblende in vein-

lets younger than all the other silicates—are of magmatic origin, and were present as original constituents of the magmas before the separation of any of the minerals began. This conclusion is in entire accord with the microscopic evidence that, although sulphides have replaced silicates, and that pyrrhotite may have been replaced by pentlandite and chalcopyrite in turn, there is not the slightest indication that these conditions were brought about by metasomatic processes after the rocks had crystallized.

By whatever process the association of pyrrhotite, pentlandite, and chalcopyrite was brought about, it has already been made clear that all of these sulphides must be regarded as belonging to the magmatic period. From what has been said concerning the replacement, under magmatic conditions, of silicate by silicate, and, to a less extent, of silicate by sulphide, it will be seen that there can be no serious objection to the application of the same principle to account for the relations of the sulphides to one another. That is, that pyrrhotite was first partly replaced by pentlandite and later both were in part replaced by chalcopyrite. If the association of the three sulphides be regarded merely as intergrowth which took place at a time when all had separated from the magma but were still liquid, though not miscible with one another, it is difficult to see why the definite paragenesis—pyrrhotite, pentlandite, chalcopyrite—should always be found rather than other possible combinations. The early separation of pyrrhotite is naturally to be attributed to its slight solubility in the molten silicates, but, with the changing proportions of the liquid components in the cooling magma, some of the pyrrhotite might go back into solution, in obedience to the law of mass action, at the time when pentlandite and chalcopyrite were beginning to separate, and might reappear among the last minerals to crystallize.

In attempting to apply these principles to the broader problem of the origin of the ore deposits, one is hampered by the meager information concerning the field relations. Enough is known, however, to permit certain general conclusions that are in accord with both field relations and the facts brought out in the microscopic study.

As far as one can tell the individual deposits that attracted early prospecting consisted merely of portions of the more basic rocks that were especially rich in metallic sulphides. It is not possible to say whether the rocks carrying the ores were parts of large masses or were in the form of small intrusive bodies, but observations in the neighborhood of the old workings show that rocks of several different kinds are present within areas of a few square rods. Thus, at the Buck mine, not only may norites, pyroxenites and peridotites be collected from outcrops within a few feet of each other, but these same rocks lie mingled together on the dumps, indicating the complex conditions found in the short distance that exploration extended below the surface. This same mingling of extreme differentiates of a gabbroitic magma is noted by Hobbs as characteristic of the whole area. One can not help believing that, at the localities where prospecting has been carried on, repeated injections on a small scale of closely related, though individually distinct, magmas took place and caused the existing complexities, rather than that the varied rock types, including the sulphides, were differentiated *in situ* from a common magma. In either case the conditions under which the crystallization of the magma took place would have been essentially the same, with the possible exception of the intrusive, where cooling may have been more rapid than in the case where the sulphides are supposed to have segregated from a larger body of magma in place. Rapid crystallization would, of course, favor the association of silicates and sulphides, while slower cooling might permit a more complete segregation of the sulphides. Although intrusion of an extreme differentiate seems to account most satisfactorily for the conditions found at Litchfield, the formation of magmatic sulphide deposits by segregation from a magma after intrusion is in every way consistent with the principles that have been discussed. Although it may be economically important to distinguish between the two types of deposit, theoretically there is no great difference between them. Both are to be attributed to the extreme differentiation of magmas that initially contained metallic sulphides in solution. In the one case

segregation did not begin until the parent magma had reached its final resting place, while in the other differentiation occurred before intrusion, and sulphide-rich and sulphide-free magmas were separately extruded from a common basin.

SUMMARY.

The Litchfield rocks are of interest because of their remarkable freshness and their intimate association with deposits of metallic sulphides. The microscope shows that pyrrhotite, pentlandite and chalcopyrite are present in all the rocks examined; that none of the silicates has suffered postmagmatic alteration; that the association of the sulphides and silicates is an original one; and that the sulphides are as essentially magmatic as the silicates. Further study of thin sections and polished specimens leads to the conclusion that, although most of the sulphides separated from solution at an early stage of the cooling of the magmas, small quantities continued to separate or to re-dissolve until the magmas had nearly crystallized. The form of the sulphide masses and their interstitial relations with respect to the silicates seems to show that, although they may have separated early from solution, they remained liquid until all the silicates had crystallized.

The conclusions reached as a result of the microscopic study are in accord with the principles of physical chemistry that may be applied to the complex systems represented by the magmas that have been described, and indicate that the sulphides were present in solution as original constituents of the magmas before final crystallization started. It is believed, however, that certain volatile constituents were also present in solution as mineralizers, and that through them the solubility of the sulphides in the molten silicates was increased.

The concentration of the sulphides is attributed to the differentiation of the gabbroitic magma before its extrusion, the sulphides and associated silicates being among the last products to be drawn from the magma basin. It is believed that the sulphide-rich rocks occur as small intrusive bodies in rocks previously extruded.

A STUDY OF SOME HEATING TESTS, AND THE LIGHT THEY THROW ON THE CAUSE OF THE DISAGGREGATION OF GRANITE.

W. A. Tarr.

INTRODUCTION.

During the past year the writer carried out a series of tests to determine the effects of heat upon Missouri granites. The work was done in the engineering experiment station of the University of Missouri, which furnished the funds for the experiments. The results obtained throw considerable light on the cause of the well-known disaggregation, at high temperatures, of granite and other rocks of more or less complex mineral composition. For that reason a statement of the results obtained is restated. The account of the experiments is published in full in Bulletin 27, Volume 15, Engineering Experiment Station Series, University of Missouri.

Experience has shown that when certain of our building and ornamental stones are subjected to high temperatures, as in the burning of a building, they are seriously damaged or entirely destroyed. The extent to which each is damaged depends upon its mineralogical and chemical composition and upon its physical properties. Granite has been noted for its marked disaggregation, and for this reason it was used in the series of experiments carried out by the writer.[1] These experiments consisted in determining the strength of the fresh granite, heating prepared cubes, two inches square, to temperatures of 500° C. and 750° C., and then cooling them, either in air or water. After a careful examination of the heated cubes they were tested to determine their strength. A series of cubes were heated to various tempera-

[1] The writer was assisted in the work by L. M. Neumann, research assistant in the Eng. Exp. Station, University of Missouri. Mr. Neumann did the heating and testing of the strength of the materials.

tures up to 1000° C. in order to determine, if possible, at what temperature the granite was most seriously damaged.

These tests were of value in showing the relationship of the strength to the temperature. In order to obtain evidence as to the cause of the disaggregation slides were made of the fresh granite and of the heated material. The examination of these and of the cubes before crushing gave valuable evidence as to the real cause. Rods of granite approximately seven and one half inches long and two inches square were heated to the same temperatures as those given above and were measured while hot, and then after cooling, the permanent expansion thus being obtained.

PREVIOUS WORK ON THE TESTING OF STONE.

Many men have made fire tests of our various building stones, but none have afterwards determined their strength or tested a series of the same rock at various temperatures. Neither, as far as the writer is aware, has the material ever been studied with the petrographic microscope before and after heating. All the common building stones have been tested, the usual method being to place the material in a furnace or build a fire around it and afterwards to throw water upon the heated stone. Only a few men have tried to control the temperatures used, or even note them. McCourt[2] has given the most complete series under temperature control. Other investigators are H. A. Cutting,[3] J. A. Dodge,[4] Jackson,[5] E. R. Buckley,[6] and R. L. Humphrey.[7] The results obtained by these men show that granite is less resistant to fire than limestone or sandstone. Likewise, coarse-grained rocks are less resistant than fine-grained ones. Syenites do not show much greater resistance to disaggregation than granites, although they are usually thought to be more resistant. As the

[2] McCourt, W. E., Ann. Rep. N. J. State Geol., 1906: 19–77.

[3] Cutting, H. A., *Am. Jour. Sc.*, series 3, 21: 410, 1881.

[4] Dodge, J. A., Minn. Geol. Surv., vol. 1, 168.

[5] Jackson, 8th Ann. Rep. State Min. of Calif., 1888.

[6] Buckley, E. R., "Building Stones of Wisconsin," Bull. 4, Wis. Geol. and Nat. History Survey, pp. 72–385. Buckley, E. R., and Buehler, H. A., Mo. Bur. Geol. and Mines, V., 11 (2): 49.

[7] Humphrey, R. L., Bull. 370, U. S. Geol. Surv.

temperatures used were usually sufficiently high to entirely destroy the stone, probably no need of making strength tests was recognized.

VIEWS NOW HELD AS TO THE CAUSE OF THE DISAGGREGATION OF GRANITE.

There are two views that are commonly held as to the cause of the disaggregation of granite. Both have been held for a long time and are found in our most recent literature.[8] The one which seems to be considered most important by some of our leading geologists looks to the minute liquid or gaseous inclusions in the quartz of the granite as the cause. Since these inclusions are only found in quartz only those rocks which contain it are thought to be seriously disaggregated. This, however, is not the case, as is shown by the work of Dodge and McCourt. The material in the fluidal inclusions is commonly water, but it may be carbon dioxide, or other gases, or liquids. On heating the enclosing material the liquids are thought to become gases which expand and finally burst the tiny cell in which they are confined, disrupting the mineral which contains the cell and shattering the rock.

The other view regards the physical factor of expansion as the most important cause of the disaggregation. It is known that the various minerals in rocks expand at different rates when heated, a process which must unquestionably set up very severe strains in the rock, or even disrupt it. This may be carried a step further and the strains set up between the outer hot portion and the cooler interior be regarded as largely the cause.

Doubtless many men have thought that both the inclusions in the quartz and the differential stresses set up in the rock have been effective in the disruption, but the writer believes that the following evidence will prove that the inclusions have no share in the cause of the disruption.

[8] See the following: Pirsson, L. V., "Rocks and Rock Minerals," p. 209. Ries and Watson, "Engineering Geology," pp. 449 and 459.

DESCRIPTION OF THE MATERIALS USED.

The material used in the tests was Missouri granite which was obtained from the various quarries at Graniteville, and Knoblick, Missouri. Some of these quarries produce building and monumental stone, while others produce mainly crushed granite and paving blocks. At least one set of six cubes was made of the material from each quarry.

The description of the granite from the A. J. Sheahan Granite Company's Quarry at Graniteville will be given in full, but only the points of importance to this paper will be given for the others.

A. J. Sheahan Granite Company, Granitville, Mo.

Megascopically, the granite is a pinkish red to dark red rock, occasionally porphyritic, and medium to coarse-grained. It consists of feldspar and quartz with a small amount of biotite, muscovite, magnetite, fluorite, and hematite. The relative proportions of the first two minerals determined by the Rosiwal[9] method are 68.7 and 31.3 per cent., respectively. The feldspar crystals average about one fourth of an inch in diameter, with an occasional phenocryst an inch or more in length. Zonal banding and Carlsbad twinning are quite common. The quartz occurs in crystals up to three eighths of an inch in diameter. In an area of four square inches several crystals with prismatic and pyramidal faces may be observed. In the larger crystals the quartz usually has a dark, translucent appearance, but where thin, it is nearly transparent, save for a slight cloudiness. The larger grains are always full of cracks. The magnetite is usually associated with the biotite from which it and the chlorite were derived. The fluorite is in purple grains, and the muscovite occurs in small books. Occasionally a grain of pyrite may be seen.

The microscope shows that the feldspar comprises orthoclase, microcline, and plagioclase, the plagioclase varying from oligoclase-andesine to andesine. The proportions of each variety vary, but the orthoclase usually exceeds the others in amount. Microcline and plagioclase are nearly equal in amount. All of the

[9] Bulletin 313, U. S. Geol. Surv., p. 173.

feldspar is strongly kaolinized, and all varieties of it contain some mineral inclusions, the plagioclase containing the most.

The quartz is especially interesting because it is the mineral that contains the fluidal cavities, if any are present. In the slide it is clear and transparent as a rule, with cracks running in various directions. Rarely these cracks are parallel, suggesting that they are along cleavage lines. Good evidence that cracks develop parallel to the cleavage planes in quartz was obtained in the study of the slides made from the heated cubes. Running in various directions in the quartz, are more or less sinuous lines of inclusion, which are sometimes parallel to the crystal faces of the quartz. They are not closely spaced, and many inclusions are scattered through the quartz, either disseminated or aggregated into clouds. It is these inclusions which give the cloudy appearance to the quartz when it is examined megascopically. The inclusions are very minute. Measurements on a great many gave diameters from 0.005 mm. to 0.00027 mm., the average being about 0.0025 mm. The inclusions consist of fluidal cavities and grains of various minerals, chiefly fluorite, magnetite, occasionally apatite, and a greenish mineral which may be biotite. The greenish mineral is not arranged in rows, but the fluorite, often showing the purple of the larger crystals, shows a marked tendency to be so arranged.

The fluidal cavities are of particular interest. Their size has already been noted. Usually they are irregular in shape, but occasionally their outline is oblong. The cavities often contain a small bubble of some gas or of air, and this bubble is sometimes in motion. The diameter of one of the largest of these "moving bubbles" was estimated to be 0.00009 mm. and was in a cavity which was 0.0027 mm. in diameter. Some cavities contained gas alone and some probably contained liquid alone. The bubbles, like the fluoride inclusions, show a tendency to a linear arrangement. The problem would be favored by a quantitative estimate of the amount of the inclusions, but it is not possible to obtain one. A careful study of all the slides was made and the following figures are merely the writer's best estimate. The in-

clusions comprise probably one per cent. of the quartz, and the fluidal cavities comprise from one half to three fourths of this one per cent. This may vary fifty per cent. either way, but it goes to show that the fluidal cavities comprise only a small amount of the quartz. This estimate is in agreement with the estimates of other investigators who have stated an opinion. The small size and the relatively small amount of the fluidal cavities should be kept in mind.

The other minerals in the granite do not present any unusual features and do not need to be described here.

A. J. Sheahan's Old Quarry, Graniteville, Mo.

This granite is in many ways similar to that described above. Its texture varies in different parts of the quarry. The proportion of feldspar and quartz is 67 and 33 per cent., respectively. The microscope shows that the inclusions are mainly in the quartz, which crystallized last. They are in rows or disseminated, and the fluidal cavities are very numerous, containing a great many moving bubbles.

Schneider Granite Company, Graniteville, Mo.

Megascopically this granite is a coarse-grained, slightly porphyritic rock of a dark red color. The estimate of the proportions of feldspar and quartz gives 72.5 and 27.5 per cent. The feldspar presents its usual features, with an occasional crystal which contains considerable chlorite. The quartz occurs in crystals which are transparent to translucent, and which show well-developed faces. The larger ones are full of cracks and some show a slight cloudiness. The minor minerals are the same as those in the other granites. Pyrite occurs in grains one sixteenth of an inch in diameter.

The microscope shows the feldspar to be microcline, plagioclase, and orthoclase, mentioned in the order of their abundance. All are kaolinized and contain minute inclusions of chlorite and fluorite. The quartz, also, contains these minerals as inclusions, and in addition it contains many fluidal cavities, few of which

show moving bubbles. The quartz is very much shattered and cracked. The biotite is iron rich, as is shown by the abundance of magnetite resulting from its alteration.

Missouri Granite Construction Company's Quarry, Knoblick, Mo.

The granite is a medium-grained, slightly porphyritic rock, of a light red color and consists of feldspar, quartz, and biotite, with phenocrysts of the feldspar and quartz. Allowing five per cent. for the minor minerals, the proportions of feldspar and quartz are 69.4 and 25.6 per cent. This is the smallest amount of quartz in any of the granites of which an estimate was made. The quartz occurs in rounded grains, more or less cracked, and is of a milky, translucent appearance.

The microscope shows that the feldspar is orthoclase and a basic plagioclase which is probably labradorite. The absence of microcline is to be noted as it does not occur in any of the slides of the granites of the Knoblick area. The quartz is often idiomorphic, and contains many inclusions of fluidal cavities and grains of various minerals. The inclusions are often in rows parallel to the pyramidal faces of the quartz. When not in rows they are disseminated through the quartz. Very few moving bubbles occur and the cavities contain an occasional crystal. Apatite is quite common, another point of difference between this granite and that of the Graniteville area.

Milne and Gordon Quarry, Knoblick, Mo.

The granite is a reddish to grayish, medium-grained rock consisting of feldspar, quartz, and biotite. The feldspar is pink to red, and the larger crystals show a zonal structure. The quartz is in smaller crystals than the feldspar and is usually very much shattered. It is transparent to translucent. The ratio of the feldspar to the quartz is 69 to 27 per cent. The biotite occurs in small crystals. The microscope shows that the feldspar is largely orthoclase with a small amount of basic plagioclase. Both are very much kaolinized. The quartz contains many fluidal cavities

and mineral inclusions. The former are large, often contain a large bubble, and are arranged in rows. Mortar structure is often seen in the quartz. The biotite is more or less altered to chlorite and magnetite.

Gilsonite Quarry, Knoblick, Mo.

This granite is a grayish, medium-grained rock, with an occasional phenocryst of feldspar, and with small segregations of biotite and hornblende up to an inch or more in diameter. The feldspar and biotite predominate in the rock, there being only a small amount of quartz.

The slide does not show any unusual features under the microscope. The feldspar is kaolinized and the orthoclase shows zonal banding. The quartz contains few inclusions of fluidal cavities. The biotite is abundant and is more or less altered to chlorite and magnetite. There is much apatite in the slide.

RESULTS OF PHYSICAL TESTS.

Before discussing the results of the study it would be well to briefly summarize the results of the physical tests. The crushing strength of the various materials used is given in the following table:

	Pounds per Sq. In.
A. J. Sheahan Granite Co., Graniteville, Mo	26,030
A. J. Sheahan Granite Co., Graniteville, Mo. (Old Quarry)	27,000
Schneider Granite Co., Graniteville, Mo	31,290
Schneider Granite Co., Graniteville, Mo. (paving block material)	34,960
Missouri Granite Construction Co., Graniteville, Mo	28,845
Milne and Gordon Co., Knoblick, Mo	25,100
Gilsonite Granite Co., Knoblick, Mo	34,875

The heating tests were made in a gas muffle furnace and the temperature read by a La Chatelier thermo-couple pyrometer. Two-inch cubes were used. Four of them were put into the furnace and the temperature was raised to 500° C. and held at approximately this temperature for thirty minutes, when two cubes were removed and one was air-cooled and the other was plunged

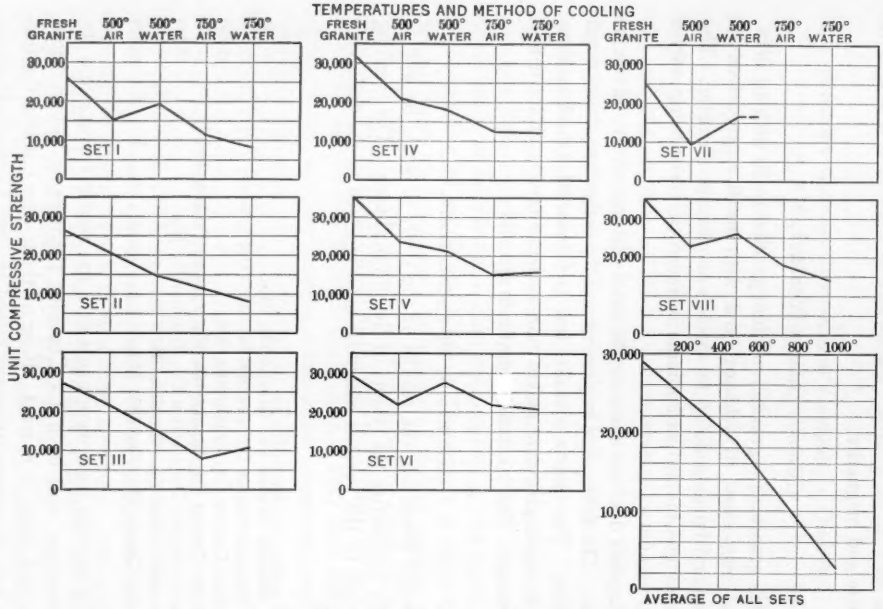

FIG. 51. Curves showing the strength of the granite at the temperatures used. For completeness the average curve includes the rocks heated to 1000° C. It shows that the decrease in strength is approximately uniform. Compressive strength in pounds per square inch. Temperatures in Centigrade degrees.

into a stream of cold water. The temperature was then raised to 750° C. and held for thirty minutes, and the remaining cubes were then removed and treated as were those described above. The results of the strength tests are shown graphically in Fig. 51. The last curve, which is almost linear, shows that the loss of strength from heating is uniform, the total average loss of strength for the series being 18,270 pounds per square inch. Such a loss practically means the destruction of the granite.

The results indicate that the plunging of heated granite into water does not cause so great a loss of strength as is commonly supposed, for in four of the eight series the specimens which were heated to 500° C. and cooled in water show a higher crushing strength than do those which were cooled in air.

The graphs of Fig. 52 show the results of heating a series of

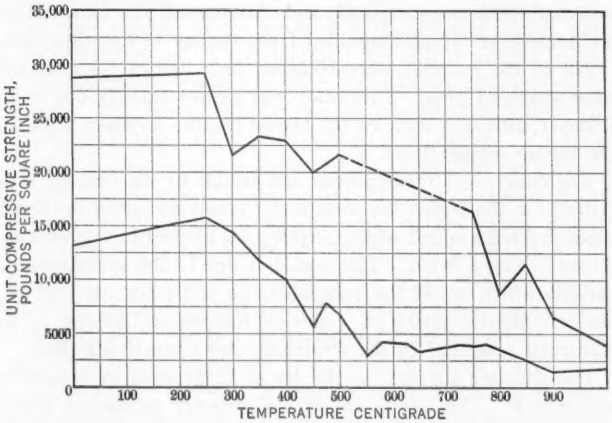

FIG. 52. Curves showing the compressive strength of cubes which were heated to various temperatures. Upper curve polished cubes from Missouri Granite Construction Co. Lower curve unpolished cubes from Sheahan's quarry.

cubes of the same material to various temperatures. The strength declines rapidly to about 500° C., or 600° C., and at 800° C. the stone is rendered worthless, retaining only ten to fifteen per cent.

average curve includes the rocks heated to 1000° C. It shows that the decrease in strength is approximately uniform. Compressive strength in pounds per square inch. Temperatures in Centigrade degrees.

of its original strength. There appears to be no definite point at which the granite shows a sudden loss of strength. It seems rather to be a gradual change. The granite from Sheahan's Quarry was tested for its permanent expansion. The results give an average permanent expansion at 500° C. of .00483 inches, or .000966 inches for one degree, and at 750° C. .01299 inches, or .0000173 inches for one degree. These values are comparable to those of other determinations.

THE EFFECTS OF HEATING ON THE GRANITES.

The study of the heated cubes before crushing brought out many points of interest and value in determining the cause of the disaggregation of granite. The polished faces of the cubes were excellent for study of the effects of the heat. This study was made both megascopically and with the aid of a Leitz binocular microscope which magnified from twenty to fifty-five times.

All of the granites were bleached to a lighter color, usually some shade of pink. This color was almost entirely due to the feldspar, although some of the biotite became a golden brown at the higher temperatures.

The cubes were made porous and friable by the heating, especially so at the higher temperatures. When scratched the heated cubes emitted a sound which Buckley has likened to that obtained on scratching a brick. This sound is due to the permanent expansion which causes the minerals to be under tension, and each one acts like the string of a musical instrument, picking up the vibrations produced by the scratching and intensifying them.

The polished surface usually has a shagreened or roughened appearance. The biotite shows the greatest permanent expansion. It bulges above the surface. The feldspar, also, shows some expansion when the cleavage planes are inclined fifty degrees or less.

The important features, however, are the size of the cracks and their relationship to the various minerals. Usually the cracks go around all minerals which are less than 1.5 mm. in diameter, but they cut across the larger ones. They are apt to

go around the grains in the coarse-grained rocks. There was at least one large crack in nearly all cubes and occasionally there were two or three. These were larger near the border and were often centrally located in the cube. Such cracks deviated very little from a straight line, passing through all minerals in their way. The base of the cube which rested on the muffle was usually badly cracked. The smaller cracks were controlled by the physical properties of the minerals, such as cleavage and twinning planes. As feldspar has two good cleavages and often occurs in this granite as Carlsbad twins it contains many cracks. The cleavage lines in the feldspar are very prominent in the material heated to 750° C. The contacts are, of course, a line of weakness and cracks are developed along them everywhere, but they are especially noticeable when the crystal is thin and lies on the surface of the cube.

The rapid cooling of the surface of those cubes which were water-cooled resulted in developing a system of minute cracks perpendicular to the surface of the cube and about one millimeter in length. As a result, the surface is covered with a series of polygonal rods from .05 mm. to .5 mm. in diameter. The same method of cooling often produced cracks parallel to the surface. This was especially true in the quartz. Minute, incipient cracks are frequently developed along the edges of the quartz grains, and many extend a millimeter or more toward the interior.

The lines of inclusions are merely the edges of planes which contain the inclusions, and theoretically this plane should be a line of weakness. For this reason careful examination was made to see whether they exercised any control over the direction of the cracks in the quartz. It was found that the cracks were just as abundant in those crystals which contained no inclusions as in those which did, and that the cracks crossed lines of inclusions in all directions. Further, it was found that the quartz often contained cracks which were parallel to the pyramidal faces of the crystals, thus showing that they were controlled by the cleavage of the quartz. The conclusion from this part of the study was that the physical properties controlled the direction of the cracks, where the direction was controlled at all.

RESULTS OF THE MICROSCOPIC STUDY OF THE HEATED GRANITE.

Slides for miscroscopic study were made from the heated rocks. The cubes which had been tested were used in making the slides whenever possible, but when this was not possible they were made from similar material which was heated and cooled in the same manner as the cubes had been. This part of the study was considered of the most importance, as the actual internal changes in the minerals could be seen. As the material was very friable it was pulled apart, more or less, along the cracks during the making of the slide, but this did not seriously interfere with the study.

The feldspars that were more or less kaolinized were much darker after heating, and the cleavage cracks were wider, due to the expansion. The brown biotite became darker and there appeared to be more hematite than in the original unheated specimen.

A very careful examination of the quartz was made, which included the size, kind, and arrangement of the inclusions, the size and continuity of any cracks, and their relationship, if any, to the inclusions. The results of the microscopic study are summarized here.

In the specimens cooled in water the quartz is usually more shattered than in those cooled in air, while it is always greatly shattered at the higher temperatures. In those specimens heated to 900° C. the quartz consists of a mass of small polygonal fragments, the smallest being .08 mm. in diameter. The feldspar is much shattered at the higher temperatures, but the cracks are controlled by the cleavage.

An interesting feature noticed in those rocks heated to 850° C. or 900° C. was a wavy extinction between crossed nicols. This occurred in both the quartz and feldspar, and is further evidence of the strains set up in the minerals by the heating, for these specimens were not crushed. There was just a suggestion of a wavy extinction in one slide of a rock heated to 750° C.

The cracks are found in all the minerals in the slide. The smaller grains of quartz are often as badly shattered as the larger ones and are usually free from inclusions. The cooling in water seems to cause more shattering than the heating alone does. The

development of incipient cracks parallel to the crystal faces is a very significant fact, as it indicates that the physical properties of the quartz are the controlling factors in their formation. These incipient cracks often intersect at an angle of 120°.

The inclusions in the quartz remain practically unchanged. The fluidal cavities are more easily recognized than they were in the slide of fresh material, because they have broader and darker borders, suggesting that many of them have become gaseous. A crack may cross a cavity, and the cavity differs in no way from those near it which are not cut by cracks. As some of the inclusions are arranged in lines, it is to be expected that a crack might follow one, as it should be a plane of weakness. This was found to be the case, but the crack might follow it for a short distance and then leave it or continue parallel to it. The cracks intersect the lines of inclusions at all possible angles and may even lie between two large lines of inclusions. Occasionally the lines of inclusions are parallel to a possible pyramidal face and then the weakness due to the inclusions is added to that of the possible cleavage of the quartz. But what is most important in this study is the fact that the cracks are no more numerous in the quartz crystals containing disseminated inclusions than they are *in the quartz crystals which are free from inclusions.* In the highly shattered grains, as in the material heated to 850°–900° C., the cracks are so numerous that they of necessity follow some of the lines of inclusions. On the whole, the writer concludes that the inclusions, whether in lines or disseminated, do not control the direction of the majority of the cracks. This conclusion is also in agreement with that resulting from the study of the heated blocks.

CONCLUSIONS REACHED AS TO THE CAUSE OF THE DISAGGREGATION OF GRANITE.

The numerous cracks which developed in the granite and its great loss of strength are evidences of the disaggregation of the rock when heated to high temperatures. The wavy extinction under crossed nicols and the ringing sound emitted on scratching

the heated cube are further evidences of the strains that are produced in the rock by the heating. This marked disaggregation, at even moderate temperatures, must have its cause in the individual minerals and in their relationships. There is also a cumulative effect which is important in large blocks.

In the individual minerals it has been thought that the molecular structure, the inclusions, and the unequal expansion of the minerals are the controlling factors in the changes resulting from heating.

Effects of Molecular Structure.

The granites studied consisted dominantly of two minerals, feldspar and quartz, with only a minor amount of other minerals. Their proportions average about 69.3 per cent. of feldspar and 28.9 per cent. of quartz. There being practically but two minerals greatly simplifies the study, as the cause of the disaggregation must lie in these two minerals. As has been noted above, feldspar has two good cleavages at nearly right angles to each other and often has twinning planes, all of which are lines of weakness in the mineral and which would be followed by cracks. This is actually the case as the cracks follow these lines in all the slides studied. When the feldspar is greatly altered to kaolin the cracks may cross the kaolinized part of the mineral in any direction. The larger cracks are especially apt to follow the Carlsbad twinning planes if any are present.

The quartz on the other hand does not possess a good cleavage. In reality it does have a fair cleavage parallel to the face "*r*," and it develops a series of fractures parallel to the rhombohedral faces or the prismatic face on sudden change of temperature, as on being plunged into water after being highly heated. The incipient parallel cracks, so common in the slides, are these parallel fractures or cleavages, and are due to the heating and cooling. In the main, however, the cracks in the quartz are very irregular, crossing the crystal in all directions. Many of the cracks were original, that is, were in the fresh granite, but in those heated to the higher temperatures they are the result of the heating.

Another factor which might be important in directing the course

of a given crack in the quartz is the presence of the inclusions, especially of those which are arranged in lines or rows. This arrangement is really along a plane which should be a plane of weakness in the crystal, and the crack should take advantage of this weakness and follow it. The conclusions reached above indicate that there is apparently no genetic connection between the cracks and the inclusions. They intersect each other at all angles and may even be parallel and close together. It is to be expected that those cracks which intersect the lines at small angles or parallel them would take advantage of this weakness, especially in view of the fact that quartz has only a weak directional effect on the cracks.

The conclusion is reached, therefore, that the molecular structure exhibited in the cleavage and twinning planes, controls the direction of the cracks when there is a determinative control. The presence of possible planes of weakness due to a linear arrangement of inclusions does not appear to influence the position of the cracks.

The Effect of the Contents of Fluidal Inclusions.

The above discussion related to the presence of the plane of inclusions as a possible source of weakness in the crystal, but the cause of the disaggregation has been thought to be due to the material in the inclusions, so it is necessary to examine this effect.

The presence of liquids and gases as inclusions in quartz has long been known. The chief of these are water and carbon dioxide, either in liquid or gaseous form. Only very small amounts of other gases occur. The size of the cavities which contain these materials is very small, rarely over .02 mm. in diameter and usually much less. The moving bubble is, of course, much smaller. An approximate estimate of the amount of fluidal inclusions gives from one half to three fourths of one per cent. The estimate is not regarded as having much value save as indicating the small amount of the inclusions, and it may be very widely in error. Other men have found the same difficulty in forming an estimate, but all agree in thinking that the amount is very small. Quantitatively, then, the effectiveness of the fluidal inclusions, even at high temperatures, would be small.

As was stated above, not a single moving bubble was observed in a specimen of the heated granite. There seem to be two possible explanations of this: one, that the gas in the bubble has escaped, and the other, that the liquid in the cavity with the bubble has been converted into a gas. In either case the "moving" bubble would have disappeared.

For the gas to have escaped it must necessarily have ruptured the walls of the cavity in which it was confined. If it had sufficient force it might do this, as for instance, when it was heated to high temperatures, in which case the expansive force of a gas is very great, or, it might be aided by the development of a crack by outside agencies, the crack penetrating its walls. The microscope shows that those cavities which are not along cracks are in no way affected by the high temperatures. The cavity walls are not cracked and do not show a strain effect such as would be developed by pressures from within. The cavities along the cracks have, of course, lost their contents. Occasionally one of the incipient, parallel cracks would intersect a cavity, but in this case the usual dark border indicating the presence of a gas was still there, and was just as prominent as was that of its neighbor. Thus the very important fact is established that the expansive force of the material in the cavities has not ruptured the cavity walls. This, of course, proves that granite is not shattered on account of fluidal inclusions since quartz is not.

As to the second possibility, that the liquid portions may have been converted, in large part, into a gas, the evidence is not so conclusive. The cavities are darker and their margins are broader, which is a characteristic of those that are largely gaseous. The boundaries are as distinct as they are in the unheated specimens, and occasionally a large cavity contains an immovable bubble.

The Effect of the Unequal Expansion of the Minerals.

The above discussion has shown that the high temperatures to which the granite was subjected greatly weakened it and also produced numerous cracks of various sizes. The position of the cracks was due to the molecular structure, the inclusions in the minerals, especially those in the quartz, having an important effect.

The chief physical property that would be effective in producing the disruption of a rock is the rate of expansion of the various minerals.

It is well known that various minerals expand at unequal rates. Clarke[10] gives the cubic expansion of quartz as .000036 per degree and of feldspar as .000017. Thus quartz has more than twice as great a cubic expansion as feldspar, and very unequal stresses are set up in a rock that consists of these two minerals when it is heated to high temperatures. The linear expansion of a mineral differs along the different axes, and this adds its effect to the variance in cubic expansion between the minerals. Clarke gives the following data for the two minerals mentioned above. For quartz the expansion along the *c*-axis is .000008073 per degree, while along the *a*-axes it is .000015147; the ratio being nearly 1:22. For feldspar (adularia), the expansion differs along the three axes and has the following values: .000015687, .000000659, and .000002914, the ratio being 23.6:1:4.4. Thus feldspar expands nearly twenty-four times as much along one axis as it does along that of the least expansion, and four and four tenths as much along another. This marked difference in the rate of expansion in the same mineral must produce very severe strains, not only in it, but in the adjacent minerals as well. If the rate of cubic expansion holds at the temperatures used, the amount of expansion would be as follows:

	500° C.	750° C.	1000° C.
Quartz	.018	.027	.036
Feldspar	.0085	.0128	.017

Results which are comparable are obtained when the linear rates are applied to the higher temperatures and are regarded as indicating the general character of the expansion. The permanent expansion of a block seven and one half inches long heated to 500° C. is .00483 inches, and for a similar block heated to 750° C. is .01299 inches. These figures it will be noticed are comparable to those given in the table above. They show that very severe

[10] Clarke, F. W., Smithsonian Miscellaneous Collections, 14: 289, p. 17.

strains are produced in the minerals, and, of necessity, in the rock also. These strains find relief in rupturing the rock and in producing permanent expansion. The cracks in the minerals and cubes are the result of this expansion, but are produced by the varying expansion of the minerals. The disruption is further aided by the strains set up during the cooling, the outer portion cooling faster and consequently shrinking upon the hotter interior. It is this which causes the spalling of granite when it, after being highly heated, is rapidly cooled in water.

It was thought that the inversion point of quartz might be a factor in the disaggregation, and those temperatures to which the cubes were heated were chosen so as to approach this. There is a permanent expansion in the quartz in passing from alpha-quartz at 575° C. to beta-quartz at higher temperatures. Above 870° C. the beta-quartz is unstable and inverts to tridymite if the conditions are favorable.[11] Fenner states that unless a flux is present this change does not occur until a temperature of 1400° C. is reached.[12] As most granites are believed to have cooled above 575° C. and below 870° C. the first change would not be effective in this study, and the change to tridymite would not take place at the temperatures used without a flux. The strain effects noted at the higher temperatures, 850°–900° C., are in the feldspar as well as in the quartz and so cannot be interpreted as indicating a tendency to inversion. This might become affective if the granite were heated to 1400° C., but it would be destroyed by the expansion long before that point was reached.

Thus the expansion of the dominant minerals of the granite is believed to be the controlling factor in causing the disaggregation of the granite. The expansion is shown to be great and to vary in different directions, so the result is that a series of very severe strains are set up in the mineral, which find relief in developing cracks along molecular lines of weakness. When the molecular structure is not in control cracks are without determinate direction.

[11] Wright and Larsen, *Am. Jour. Sc.*, 4th series, 27: 421, 1909.
[12] Fenner, *Wash. Acad. Sc.*, 1–2; 472: 1911–12.

SUMMARY.

The disaggregation of the Missouri granites as a result of heating is due to the differential stresses set up in each individual mineral. These stresses vary in different directions because of the different rates of expansion and find relief in cracks and fractures. The stresses are cumulative and affect the rock as a whole but differ in different parts of it.

The presence of inclusions, especially of liquids and gases, whether in rows or disseminated, is not regarded as having any effect upon the resulting disaggregation, except, in so far as a series of inclusions of any nature arranged along a plane in a mineral would make that plane a line of weakness that might be followed by a crack.

EXPERIMENTS IN THE ENRICHMENT OF SILVER ORES.

LOUIS G. RAVICZ.

INTRODUCTION.

The theory of secondary enrichment was announced in 1900, in three notable papers, published almost contemporaneously by S. F. Emmons,[1] W. H. Weed[2] and C. R. Van Hise.[3] A summary of the process of enrichment of copper deposits by J. F. Kemp[4] appeared in 1906, and the criteria for the recognition of secondary sulphide enrichment were reviewed by F. L. Ransome[5] in 1910. An excellent summary by C. F. Tolman[6] and a comprehensive and detailed treatment of the subject, in which all of the previous work is discussed and correlated, by W. H. Emmons, were published in 1913. The theory as first proposed was based primarily on observation. In more recent years, however, much work toward the solution of the physical and chemical problems involved has been done in the laboratory. As this paper deals exclusively with the secondary enrichment of silver, only those papers which deal with this subject, wholly or in part, need be mentioned here. Among them are contributions by W. H. Weed, H. C.

[1] Emmons, S. F., "The Secondary Enrichment of Ore Deposits," *Trans. Am. Inst. Min. Eng.*, vol. 30, 1901, pp. 177–217.

[2] Weed, W. H., "The Enrichment of Gold and Silver Veins," *Trans. Am. Inst. Min. Eng.*, vol. 30, 1901, pp. 424–448.

[3] Van Hise, C. R., "Some Principles Controlling the Deposition of Ores," *Trans. Am. Inst. Min. Eng.*, vol. 30, 1901, pp. 177–270.

[4] Kemp, J. F., "Secondary Enrichment in Ore Deposits of Copper," ECON. GEOL., vol. 1, 1906, pp. 11–12.

[5] Ransome, F. L., "Criteria of Downward Sulphide Enrichment," ECON. GEOL., vol. 5, 1910, p. 205.

[6] Tolman, C. F., "Secondary Sulphide Enrichment of Ores," *Min. and Sci. Press*, 1913, p. 38, 141, 178.

Cooke,[7] H. N. Stokes,[8] Palmer and Bastin,[9] and F. F. Grout.[10]

The factors controlling the solution, transportation and deposition of the metals, are of great importance. Especially is this so in the case of silver as a small amount of secondary enrichment may make an otherwise valueless deposit, of commercial importance.

MINE WATERS.

A study of the behavior of mine waters is essential in an interpretation of these chemical processes. Mine waters of sulphide ore bodies generally show that the metals are in solution as the sulphates. In many of the waters of silver deposits, however, considerable amounts of carbon dioxide and carbonates are present, and the metals, especially silver, may also be in solution in this form. The waters of the upper zone are sulphuric acid waters, but the acidity gradually decreases, as the waters descend, and they become neutral and even alkaline. In his examination of fifty mine waters, recalculated by the Chase Palmer method, Hodge[11] found that twenty-two were acid, fourteen were neutral and fourteen alkaline; also that salts of the heavy metals occur in relatively large amounts in acid waters, in smaller amounts in neutral, and are practically absent in alkaline waters. Traces of gold and silver are found in the Central Tunnel and C and C waters of the Comstock lode. Both contain ferric iron. One of these waters is acid; the other is neutral. Ferric sulphate is abundant in the upper zones of ore deposits, where with dilute sulphuric acid, formed generally from the oxidation of pyrite, it exerts a potent solvent effect on the sulphides present. At depth, ferric sulphate after continued contact with the sulphides during its descent is

[7] Cooke, H. C., "Secondary Enrichment of Silver Ores," *Jour. Geology*, vol. 21, 1913, p. 1.

[8] Stokes, H. N., "Experiments on Solution, Transportation and Deposition of Copper, Silver and Gold," ECON. GEOL., vol. 1, 1906, p. 649.

[9] Palmer, C., and Bastin, E. S., "Precipitants of Gold and Silver," ECON. GEOL., vol. 8, 1913, p. 140.

[10] Grout, F. F., "Alkaline Extracts of Metallic Sulphides," ECON. GEOL., vol. 8, 1913, p. 417.

[11] Hodge, E. T., "The Composition of Waters in Mines of Sulphide Ores," ECON. GEOL., vol. 10, 1915.

reduced to ferrous sulphate. Two interesting series, showing the relative activity of minerals in decreasing acidity and in reducing iron in ferric sulphate solution, have recently been determined by G. S. Nishihara.[12]

PREVIOUS EXPERIMENTAL WORK.

A review of the work referred to above and of the literature brings forth the fact, that silver minerals with the exception of the halides, cerargyrite, bromyrite, embolite and iodyrite, and possibly also native silver, may be either of primary or secondary origin. These minerals include, not only the sulphide, but many complex compounds of silver with arsenic and antimony. In the experiments cited, the precipitate was usually the free metal, although Cooke[13] obtained some silver sulphide by the interaction of metallic silver with freshly precipitated sulphur. Palmer and Bastin[14] by precipitation with metallic sulphides obtained some sulphide but much larger amounts of the free metal. Grout[15] following up this line of work confirmed the tests of Palmer and Bastin and determined in addition, that when ferric sulphate is present in the solution, the free metal is not precipitated except by the more active sulphides, whereas the sulphide may be. Rickard[16] obtained metallic silver by precipitation with carbonaceous matter. Weed[17] states that native silver is formed in films and crystalline masses by reduction with ferrous sulphate according to the following reaction:

$$Ag_2SO_4 + 2FeSO_4 = 2Ag + Fe_2(SO_4)_3.$$

Native silver is abundant in the deposits at Cobalt, Ont., but is less prominent in the western districts of the United States. In the latter, the most important silver mineral is argentite; characteristic

[12] Nishihara, G. S., "Rate of Reduction of Acidity by Ore and Gangue Materials," ECON. GEOL., vol. 9, 1914, p. 743.

[13] *Op. cit.*, p. 25.

[14] *Loc. cit.*

[15] *Op. cit.*, p. 420.

[16] Rickard, T. A., "The Enterprise Mine, Rico, Colorado," *Trans. Am. Inst. Min. Eng.*, vol. 26, 1896, p. 978.

[17] *Op. cit.*, p. 431.

also is a long series of complex silver sulphantimonides and sulpharsenides; and it is often difficult to determine whether they are primary or secondary. Among them are proustite, pyrargyrite, miargyrite, stephanite, polybasite, and silver-bearing tetrahedrite (freibergite) and galena.

Silver is soluble in dilute sulphuric acid, but the sulphide is only sparingly attacked by the acid alone. In the presence of ferric sulphate, however, the solubility of the sulphide is greatly increased. Cooke[18] has shown that a small amount of ferric sulphate is effective and believes that the function of the ferric sulphate is to oxidize any hydrogen sulphide that may form and which would retard the further solution of silver sulphide.

In ore deposits containing abundant calcite in the gangue, the transportation of silver as the carbonate is not improbable. The normal carbonate is soluble to the extent of .031 gm. per liter[19] Johnston[20] states, moreover, that silver carbonate is soluble in water saturated with carbon dioxide at 15 degrees C., to the extent of .846 gm. per liter, or about twenty-seven times the normal saturation. The presence of even a small amount of carbon dioxide in the solution, greatly increases the solubility. It is thought the silver exists in the form of a bicarbonate.

EXPERIMENTAL WORK.

SILVER MINERALS WITH ALKALINE CARBONATES.

A series of experiments were attempted to determine whether silver, and its sulphides are soluble in alkaline carbonates, as stated by Van Hise.[21] The minerals tested were argentite, pyrargyrite, proustite, polybasite, hessite, cerargyrite, argentiferous, tetrahedrite and galena, and metallic silver. The tests were made in 150 c.c. glass stoppered bottles. Five grams of the mineral, pulverized to 80 mesh, were used in each test. Samples were prepared in duplicate. To one set was added 100 c.c. of a 1 per

[18] *Idem*, p. 12.

[19] Seidell, "Solubilities of Inorganic Compounds," 1913, p. 282.

[20] Johnston, G. S., *Chem. News*, 54, 1886, p. 75.

[21] Van Hise, C. R., "A Treatise on Metamorphism," Monograph U. S. Geol. Survey, No. 47, 1904, p. 1099.

cent. solution of potassium bicarbonate; to the second set, the same amount and strength of normal carbonate. The bottles were shaken daily. After a period of three months, 25 c.c. of the solution was taken from each and tested for silver with sodium chloride. In no instance did a precipitate form. A few drops of a strong solution of potassium iodide, which would form the very insoluble silver iodide, was added but no precipitate or even an opalescence was noted. The same minerals were then treated with a hot solution of sodium carbonate, and kept at a boiling temperature for several hours, but no silver was dissolved. From the pyrargyrite, a trace of antimony sulphide was leached, and from the proustite, considerable arsenic sulphide.

EFFECT OF CARBONATES ON SILVER SOLUTIONS.

Since calcium carbonate readily precipitates gold and copper from their solutions, it has been thought by some that calcite in a silver deposit is unfavorable to the formation of deep zones of silver enrichment. But calcite, in solutions of silver bicarbonate and silver sulphate that have concentrations of silver below a certain point, has no precipitating effect. To determine this point 10 gm. of calcite pulverized to 200 mesh was treated in a small glass stoppered bottle with 100 c.c. of silver bicarbonate solution. The silver bicarbonate was made by dissolving the normal carbonate in water containing carbon dioxide and contained 0.4 gm. of silver per liter. Precipitation of black metallic silver or the oxide began immediately. The bottle was shaken daily. At intervals small samples of the solution were removed and titrated. After one week when the action had ceased there was .1544 gm. of silver per liter in solution. The solution was allowed to remain in contact with the calcite for six weeks longer when another sample was taken and titrated. The silver content was the same. With silver sulphate solution in the presence of excess calcite, treated in the same manner, .3281 gm. of silver per liter remained in solution. When the amount of the silver was below the values given no precipitation took place. When 100 c.c. of a solution of silver bicarbonate of one half that concentration was

treated with calcite, in three weeks no silver had precipitated. Therefore, if only small amounts of silver are present in mineral waters, calcite cannot cause precipitation of the silver in the dilute solutions.

Siderite in the gangue does not necessarily prevent the development of deep zones of silver enrichment. True, the action of acid on siderite is to liberate ferrous sulphate, which would ordinarily precipitate silver as the metal. As the descending solutions carry ferric sulphate in addition to acid, some substance to reduce this must be present, as in its presence, the silver will not be precipitated. In a mixture of equal parts of ferrous and ferric sulphate considerable silver will be held in solution so that a mineral water will have to be thoroughly reduced before all of the silver will be precipitated. A bottle in which was placed pulverized siderite and to which was added ferric sulphate, dilute sulphuric acid and some silver sulphate has now stood for a month without precipitation of silver. On the addition of tetrahedrite to a portion of the solution, the ferric sulphate was rapidly reduced and the silver precipitated.

Rhodochrosite is ineffective as a precipitant of silver in dilute solutions. Manganous sulphate, formed by the action of acids on the mineral, under these conditions is not a reducing agent and would, therefore, have no effect comparable to ferrous sulphate.

Since mine waters in the deeper zones become alkaline, it is pertinent to determine the action of alkalies on silver-bearing solutions. Accordingly, dilute silver bicarbonate and sulphate solutions were treated with strong alkaline carbonate. White precipitates formed immediately in both solutions. The precipitates were filtered off and the solutions titrated for the silver content. In the bicarbonate solution, .019 gm. of silver per liter still remained; in the sulphate solution .1 gm. Both solutions were strongly alkaline to methyl orange, and contained an excess of alkaline carbonate. In dilute solutions of silver bicarbonate and sulphate, a considerable amount of the alkaline carbonate must be added before precipitation takes place. The exact reactions are not known as the state in which the silver salt exists may be either bicarbonate, the normal carbonate, or both.

The carbonates rapidly neutralize the acidity of the solutions and as a result there would be an alkaline zone at moderate depth. The point must not be overlooked that carbon dioxide is liberated in the process and that even a small amount of carbon dioxide in the solutions, greatly increases the solubility of the silver carbonate. The alkaline zone is in itself not unfavorable to the development of deep zones of enrichment. What, then, precipitates the silver in its deposits? The various reagents that may be operative are discussed below.

EFFECT OF ALKALINE SULPHIDES.

The sulphosalts of silver are unstable in the presence of hot alkaline sulphides. They are readily leached of their arsenic and antimony sulphide by such hot alkaline solutions. When pyrargyrite was treated with a hot, one half per cent. solution of sodium sulphide, the finely pulverized red powder turned black. This black residue was filtered, carefully washed and, on testing, sulphur and silver were obtained, but no antimony. On acidifying the filtrate, a red amorphous precipitate of antimony trisulphide was obtained. Proustite acted similarly to pyrargyrite and readily yielded its arsenic to the alkaline sulphide. Polybasite also acted in a similar manner, but for the removal of all the antimony a short period of boiling was necessary. Silver-free tetrahedrite and arsenopyrite were treated with hot alkaline sulphide, but no antimony or arsenic was leached from these minerals by the one half per cent. solution. With a strong solution, about three per cent., and boiling for a considerable period some antimony sulphide was leached from tetrahedrite.

Many ore deposits have doubtless formed through precipitation by hot ascending waters probably charged with alkaline sulphide, chloride and carbonate solutions of the metals. Where such waters containing alkaline sulphides, rising up through fissures and openings in the rocks, precipitate their metallic content by a decrease of temperature and pressure only, silver sulphide will probably have been deposited before the solutions have cooled to 100 degrees C., because sulphide of silver is not attacked by

alkaline solutions and is therefore stable at that temperature; but the sulphides of arsenic and antimony will not precipitate until cooler surroundings are reached because they can be readily dissolved by alkaline sulphide at lower temperatures. Under the conditions postulated that is, precipitation of the metals from alkaline sulphide solutions by decrease in temperature and pressure only, the sulphosalts of silver could not be primary minerals. Alkaline sulphide solutions of stibnite and orpiment are stable at room temperatures in airtight containers and only when acidified or exposed to the atmosphere, do the sulphides of arsenic and antimony separate out. Indeed, the home of stibnite is in deposits formed near the surface, although it is not exclusively confined to such occurrences. However, if precipitation takes place by the mingling of hot ascending alkaline sulphide and carbonate waters with downward percolating acid or oxygenated waters, then, simultaneous precipitation of the component sulphides may result in the formation of complex silver minerals. As acid conditions do not penetrate to great depths below the surface, deposits in which the sulphosalts of silver are primary are those formed at shallow depth, and, in these, the sulphosalts might occur intergrown with stibnite and other primary minerals characteristic of such deposits. In ore deposits known to have formed at intermediate or greater depth, beyond the active influence of superficial acidic waters, it is probable that these minerals are secondary; and we may classify them with kaolin, alunite, marcasite, wurtzite and possibly other minerals which may be primary in deposits formed at shallow depth, but they are generally secondary when found in veins of the intermediate or deep zone.

PRECIPITATION OF SILVER MINERALS.

Metallic Silver.

Ferrous sulphate acting on a solution of silver sulphate or silver carbonate readily precipitates metallic silver which comes down as a cloud of silvery flakes, in the sulphate solution, and as a finely divided black precipitate in the carbonate solution. The action, however, is not complete; a considerable amount of silver remains

in solution, due undoubtedly to the presence of ferric sulphate which is formed in the process. The reactions may be written as follows:

$$Ag_2SO_4 + 2FeSO_4 = 2Ag + Fe_2(SO_4)_3,$$
$$Ag_2CO_3 + 3FeSO_4 = 2Ag + FeCO_3 + Fe_2(SO_4)_3.$$

These reactions take place in very dilute solutions; a solution of ferrous sulphate, containing 10 parts per million readily precipitated silver from a .1 per cent. sulphate solution. The action was not complete. When the sulphides, chalcopyrite and pyrrhotite were added to portions of the solution, the silver was entirely precipitated, slowly with chalcopyrite and very rapidly with pyrrhotite.

This condition is analogous to that in nature where ferric sulphate is reduced to the ferrous state, as the solutions descend, by reaction with the primary sulphides present. Moreover, as conditions in depth are favorable for the formation of ferrous sulphate at the expense of the ferric, all the silver will eventually be precipitated, either as the metal by ferrous sulphate or as argentite by the sulphides present, or possibly as a mixture of the two. Such a condition seems to have existed at Creede, Colo., where in depth are found mixtures of native silver and secondary argentite. Native silver has a wide range, for it occurs in the oxidized zone, derived from argentite and the sulphosalts by weathering and oxidation, and it is found deposited with calcite and barite at depths of a thousand feet below the surface, and hundreds of feet below the water level as at Aspen, Colorado.

Argentite.

Argentite and the sulphosalts, not native silver, are the commonest and most important secondary silver minerals in many deposits. Argentite may possibly be formed at shallow depths by the action of hydrogen sulphide and some metallic sulphides on the silver-bearing solutions. Wells[22] has shown that the action of dilute sulphuric acid on pyrrhotite, galena and sphalerite liber-

[22] Wells, R. C., quoted by W. H. Emmons, Bull. U. S. Geol. Survey, No. 529, p. 59.

ates hydrogen sulphide, which will precipitate silver sulphide from highly dilute solutions. It is somewhat doubtful, however, whether the dilute acid solutions as found in nature will be effective in liberating hydrogen sulphide from all of the sulphides. For instance, sphalerite and galena, as will be discussed later, are weak or inactive in their precipitation of silver from dilute sulphuric acid solutions. On the contrary pyrrhotite is quite active. At slightly greater depths, metallic sulphides, or alkaline sulphides formed by alkalies reacting with metallic sulphides, may precipitate silver sulphide. The action of ferrous sulphate, and some sulphides in the absence of ferric sulphate, is to precipitate silver as the metal, but under suitable conditions, this metallic silver may be changed to a sulphide or sulphosalt.

When a strip of silver was suspended in a solution of alkaline sulphide, a tarnish of black silver sulphide formed on the metal. In less than a month, the silver was coated with a black finely crystalline aggregate which had penetrated half way through the strip. In some places, the strip was entirely eaten away. In a similar manner when a strip of silver was suspended in a solution of sodium sulphantimonite, made by dissolving stibnite in alkaline sulphide, a red tarnish coated the silver, and in the same time, it also showed a finely crystalline surface. Some of this material was carefully removed and its streak tested. It gave a ruby-red streak, resembling that of pyrargyrite.

Whether some of the argentite and pyrargyrite are formed in nature in this way is not known although it is possible. Pseudomorphs of cerargyrite, ruby silver, argentite and stephanite after native silver are mentioned by Dana.[23] For this replacement, the conditions necessary must be alkaline solutions acting on the sulphides and then coming in contact with native silver. To test this theory further, crushed pyrite and pyrrhotite were placed in separate bottles, to which was added 100 c.c. of a 1 per cent. solution of alkaline carbonate. A strip of silver was then suspended in the liquid. In six weeks a black tarnish had appeared on each, faint in the case of pyrite, deep with pyrrhotite.

[23] Dana, "System of Mineralogy," 6th ed., p. 20.

FORMATION OF THE DOUBLE SALTS.

The formation of the double sulphides of silver is a closely related problem. By precipitation, in a solution of silver nitrate with potassium sulphantimonite, K_3SbS_3, I. Pouget[24] obtained the amorphous compound Ag_3SbS_3, equivalent in composition to pyrargyrite. The recent work of Grout[25] indicates that these salts are probably the result of intermingling solutions of the metals in an alkaline environment. On treating a sodium carbonate extract of stibnite with a sulphuric acid solution of silver containing more than enough silver to unite with the antimony present, he obtained a compound, the analysis of which indicated approximately the composition of stephanite $(Ag_2S)_5.Sb_2S_3$. The resulting solution was slightly acid.

Some further work along these lines was undertaken. A solution of sodium sulphantimonite was made by boiling an excess of stibnite with sodium sulphide. To this solution, which was diluted before using, was added neutral silver sulphate, in such amount that the resulting solution would contain an excess of antimony sulphide. A reddish brown solution immediately resulted which contained a colloidal precipitate. As such colloidal precipitates result from reactions between two chemical compounds in the absence of electrolytes, the precipitate was readily coagulated when sodium sulphate was added, and settled as a reddish brown gelatinous mass. The resulting solution contained no silver, gave an alkaline reaction with methyl orange, and, on acidifying, a precipitate of antimony sulphide was obtained, indicating that antimony was in excess. The precipitate was analyzed and found to have the following composition, Ag 58.8 per cent., Sb 24.3 per cent., S 16.7 per cent., which closely approaches the composition of pyrargyrite. In a similar manner, by the use of an alkaline sulphide extract of orpiment, a compound approaching proustite in composition was obtained. The same compounds resulted when the carbonate solution was used in place of silver sulphate. The reactions involved probably are:

[24] Pouget, I., *Compt. Rend.*, vol. 124, 1897, p. 1518.
[25] *Op. cit.*, p. 425.

$$3Na_2S + Sb_2S_3 = 2Na_3SbS_3,$$
$$2Na_3SbS_3 + 3Ag_2SO_4 = 2Ag_3SbS_3 + 3Na_2SO_4.$$

When the above conditions were varied by having the silver in excess of the amount needed to combine with the antimony present, the resulting compound was variable in composition. The average silver content of several precipitates was 71.6 per cent.

Since arsenic sulphide is soluble in alkaline carbonate, whereas antimony sulphide is relatively insoluble, the presence of carbonates in mine waters may tend to delay the formation of secondary arsenical sulpho-minerals. A mixture of sodium sulphantimonite and sodium sulpharsenite containing equal parts of antimony and arsenic sulphides was made by mixing alkaline sulphide extracts of stibnite and orpiment. To this solution was added alkali carbonate and also a solution of silver sulphate in such proportions that either the antimony or arsenic sulphide was in excess of the amount needed to precipitate all the silver. The resulting precipitate contained abundant antimony and only a trace of arsenic. Furthermore, as stated above, when pyrargyrite and proustite were treated with hot alkaline carbonate, only a trace of antimony sulphide was leached from pyrargyrite, whereas considerable arsenic sulphide was dissolved from proustite. These relations may explain the abundance in nature of the antimonial minerals, pyrargyrite, polybasite and tetrahedrite as compared with the corresponding arsenical minerals proustite, pearceite and tennanite, which are comparatively rare.

For the formation of the sulphosalts in the manner outlined above, the following conditions appear to be necessary. Arsenic or antimony must be present in solution derived from the arsenic and antimony minerals by the action of alkaline solutions. This is possible, for according to Grout,[26] dilute alkaline carbonate solutions vigorously attack metallic sulphides. Furthermore, traces of arsenic and antimony are found in several neutral and alkaline mine waters. This solution could take place only in an alkaline environment, as acids liberate antimony and arsenic sulphide from alkaline solutions. If now a solution of silver meets this alkaline

[26] *Idem*, p. 429.

solution of antimony sulphide, a compound results whose composition depends on the relative amounts of silver and antimony present. At the top of the alkaline zone, the silver is likely to be in excess, which would result in the formation of polybasite and stephanite. Above these, in the neutral zone, secondary argentite is the more probable. At slightly greater depth in the alkaline zone, conditions will be more favorable for the formation of alkaline solutions of arsenic and antimony sulphides and the precipitate with silver will be proustite and pyrargyrite. If, however, in this alkaline zone, antimonial minerals only sparingly occur, polybasite and stephanite, those minerals with the higher silver content will form. If no minerals containing arsenic and antimony are present, only argentite can form. A hypothesis of mingling solutions, and an alkaline zone at moderate depth is to be considered in the formation of secondary minerals at low temperatures. Alkaline mine waters are not rare below the zone of oxidation. In fact some of the waters recalculated by Hodge[27] as alkaline were collected within 400 feet of the surface. Deep waters of acid reaction are rare.

The occurrence in nature of these sulphosalts strongly suggests a genesis by the above method. In the Granite-Bimetallic mine at Phillipsburg, Mont., according to Emmons and Calkins,[28] pyrargyrite lines vugs or occurs in small veinlets that cut across the banding of the ore. At Tonopah, Nevada, according to Spurr,[29] it coats crevices that cut the primary ore. On the occurrence of pyrargyrite at Lake City, Colo., Irving and Bancroft say:[30]

"Ruby silver occurred, so far as could be learned, in all of the mines at the plane of demarcation between sulphides and oxides and in generally decreasing quantity, to several hundred feet below this level. Along

[27] *Loc. cit.*

[28] Emmons, W. H., and Calkins, F. C., "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," Prof. Paper U. S. Geol. Survey, No. 78, 1913, p. 204.

[29] Spurr, J. E., "Geology of the Tonopah Mining District, Nevada," Prof. Paper U. S. Geol. Survey, No. 42, 1905.

[30] Irving, J. D., and Bancroft, Howland, "Geology and Ore Deposits near Lake City, Colo.," Bull. U. S. Geol. Survey, No. 478, 1911, p. 63.

cracks and fissures it occurred in isolated masses to great depths—for instance, at 1,200 feet in the Golden Fleece and at 1,300 feet at the Ilma. These deep occurrences are, however, uncommon and merely indicate the presence of some easy line of access for downward-moving solutions. Ruby silver has probably resulted from the solutions of silver and antimony obtained by the decomposition of the tetrahedrite and possibly to some extent also from the argentiferous galena. The chemistry of both the solution and reprecipitation of the antimonial and arsenical sulphur compounds has not yet been worked out in sufficient detail to permit a statement of the probable steps of the process, but the geological facts show that it has occurred. The proofs of the secondary character of the ruby silver are: (1) Its restriction in quantity to the upper levels of the mines. (2) Its invariable occurrence as the latest deposited mineral in the veins, either in cracks or crevices in shattered primary ore or as crystals in cavities. (3) Its occurrence only in isolated bunches in deeper workings, where its origin is probably due to the presence of water channels that permit the downward percolation of water from above. (4) Its complete absence from the great mass of deep-seated ore."

Although there is no invariable rule respecting the relations of these secondary silver minerals, we may expect in some places to find them occurring in overlapping horizons with argentite above, followed in regular downward order by polybasite, stephanite and pyrargyrite and proustite. At the Granite-Bimetallic mine, the deeper secondary ores contain very little argentite or native metal, the richer minerals being almost exclusively the dark and light ruby silver. At Georgetown according to Spurr, Garry and Ball:[31]

"Below the zone where soft secondary sulphides occur and irregularly overlapping the lower portion of this zone the rich ores contain polybasite, argentiferous tetrahedrite, and ruby silver, better crystallized and more massive than the pulverulent sulphides but also subsequent in origin to the massive galena-blende ore. These richer ores diminish in quantity as depth increases, though gradually and irregularly, so that the lower portion of the veins contains relatively less silver and lead. The best ore in most veins has been found in the uppermost 500 feet, although good ore extends locally down to 700 or 800 feet, and in the Colorado

[31] Spurr, J. E., Garrey, G. H., and Ball, S. H., "Economic Geology of the Georgetown Quandrangle," Prof. Paper U. S. Geological Survey, No. 63, 1908, p. 144.

Central and to a minor extent in other veins down to a thousand feet or more."

At the Banner mine, near Silver City, Idaho, rich pockets of argentite ore in a gangue of pyrite, kaolin, quartz and calcite were mined at shallow depth. Below these, the principal ore minerals were pyrargyrite and proustite with little or no argentite.

ACTION OF METALLIC SULPHIDES.

The experiments by Palmer and Bastin[32] have a bearing here. By treating several minerals with silver sulphate in a neutral solution, they obtained a precipitate of metallic silver; in some instances a mixture of the sulphide and the metal. In order of activity they have grouped the minerals in the following manner:

Very strong: chalcocite, niccolite.

Strong: covellite, enargite, bornite, tennantite, tetrahedrite, alabandite, and possibly cobaltite.

Moderate: smaltite, marcasite, pyrrhotite, chalcopyrite, arsenopyrite.

Weak or inactive: cinnabar, stibnite, pyrite, galena, millerite, sphalerite, jamesonite, orpiment, realgar. F. F. Grout[33] has determined a series in which acid is present in the solution and which is approximately the same. In several experiments with silver carbonate in the presence of a few of the above minerals, similar action was noted. Tetrahedrite and chalcocite rapidly precipitated silver from the solution, whereas, pyrite was practically inactive.

In the above experiments, the precipitate as mentioned was the free metal. According to Grout,[34] however, the presence of ferric sulphate inhibits the formation of the free metal, and the silver is then precipitated as sulphide by an exchange of metals in the mineral. This conclusion is supported by the fact that in most cases, the metal of the mineral used as a precipitant was found in solution. In one of the experiments performed with

[32] *Op. cit.*, p. 153.
[33] *Op. cit.*, p. 417.
[34] *Idem*, p. 420.

the carbonate of silver solution in the presence of chalcopyrite, all of the silver was precipitated. On the addition of ferric sulphate, some silver was redissolved. Some of the sulphides, notably chalcocite, are so active that they precipitate free silver from its solutions even though ferric sulphate is present.

As shown above, calcite, rhodochrosite and the carbonates, with the exception of siderite, have no direct precipitating effect on the dilute solutions of silver; indirectly they rapidly neutralize acidity, resulting in neutral or alkaline conditions at moderate depth. Nephelite, leucite and possibly the zeolites, if found in ore or wall rock, would have the same effect, though not so pronounced. In such surroundings the silver may be precipitated as the native metal by organic matter or by ferrous sulphate in the absence of ferric sulphate; as the sulphide, by alkaline sulphide, or the metallic sulphides, or as the sulphosalts by alkaline extracts of arsenical and antimonial minerals. The presence of siderite in the gangue may aid in suppressing deep zones of enrichment. It rapidly neutralizes acid and with acid liberates ferrous sulphate. It does not, however, reduce the ferric sulphate present, and in its presence the silver will not be precipitated from dilute solutions by siderite alone. If, in addition, sulphides are present, precipitation will take place. In a paper on the Caledonia mine of the Coeur d'Alene, Earl V. Shannon[35] noted the occurrence of native silver in sideritic ore. The sulphides present are chalcopyrite, galena and tetrahedrite, the latter is nearly everywhere present in the ore.

In the presence, then, of the above listed "active" sulphides, shallow zones of enrichment are to be expected; in their absence, deeper zones. It is noteworthy that the sulphides active in the precipitation of silver from its solutions, are those which readily neutralize acidity and reduce iron in ferric sulphate solution as determined by G. S. Nishihara.[36] As a general rule, silver sulphide enrichment under favorable conditions is rarely

[35] Shannon, Earl V., "Secondary Enrichment in the Caledonia Mine," ECON. GEOL., vol. 8, 1913, p. 565.

[36] *Op. cit.*, pp. 745 and 749.

found to be effective more than 1,000 feet below the surface on account of the rapid rate at which silver is precipitated from its solutions by many substances. On the contrary many of the Mexican silver bonanzas extended to greater depth, in several instances at Pachuca and Real Del Monte[37] to 1,650 feet; but to what extent they are the result of secondary enrichment processes is not known.

SUMMARY.

Silver is not dissolved from silver minerals by alkaline carbonates at room temperatures. Metallic silver also is insoluble in alkaline carbonates. Hot solutions of alkaline carbonate do not dissolve silver from argentite or pyrargyrite. From pyrargyrite a trace of antimony sulphide is dissolved, from proustite considerable arsenic sulphide.

Below a certain point of concentration of silver bicarbonate and silver sulphate, in the presence of an excess of calcite, no silver is precipitated. In solutions containing less silver than these concentrations, silver is not precipitated by calcite. Siderite, with acid, though liberating ferrous sulphate, does not reduce the ferric sulphate present, and in the absence of sulphides will not precipitate silver and halt the downward enrichment of the metal. Rhodochrosite is likewise ineffective. Alkalies, such as sodium carbonate, do not entirely remove the silver from solutions of silver bicarbonate and sulphate with all these carbonates a considerable quantity of silver remains in solution, which is precipitated only when sulphides are present.

A hot dilute solution of alkaline sulphide readily leaches the antimony sulphide from pyrargyrite, leaving a fine black powder of silver sulphide. The action on polybasite is similar, but not so rapid. Arsenopyrite and tetrahedrite are not so affected by the dilute alkaline sulphide. These experiments, supported by field observations, justify the conclusion that the sulphosalts of silver may be primary in deposits formed at shallow depths, but are generally secondary in deposits formed at intermediate or greater depths.

[37] Halse, Edward, "Deep Mining in Mexico," *Trans. Inst. Min. and Met.*, vol. 3, 1895, p. 420.

Ferrous sulphate in a solution as dilute as 10 parts per million, readily precipitates metallic silver from its solutions. Due however to the formation of ferric sulphate in the process, the precipitation is not complete, but quickly becomes so in the presence of metallic sulphides.

Argentite may be formed by the action on silver-bearing solutions of hydrogen sulphide, of metallic sulphides in the presence of ferric sulphate, or alkaline extracts of metallic sulphides.

Metallic silver in a solution of alkaline sulphide rapidly takes on a black tarnish, while silver in a solution of sodium sulphantimonite takes on a red tarnish, suggesting the formation of argentite and pyrargyrite respectively.

When an alkaline sulphide extract of stibnite was added to a solution of silver sulphate, in such proportions that the antimony was in excess, and the resulting mixture alkaline, an amorphous compound was obtained, which corresponded in composition to pyrargyrite. In a similar manner, by using an extract of orpiment, a compound approaching proustite was the result. By varying the proportions of the two solutions, in such a manner that after mixing the silver was in excess and the solution slightly acid, a compound resulted which was intermediate in composition between polybasite and stephanite.

Metallic sulphides in the absence of ferric sulphate, precipitate from silver-bearing solutions some sulphide, but an abundance of free metal. In its presence the silver is precipitated as the sulphide, by an exchange of metals. A few very active sulphides precipitate the free metal even in the presence of ferric sulphate, but only after the ferric sulphate is reduced.

APPLICATION TO ORE DEPOSITS.

The principal value of the theory of secondary sulphide enrichment is its utilization in the exploration of ore deposits. The processes are influenced by many factors. Among them are temperature, rainfall, altitude and relief. For the recognition of the process, one is recommended to a review by F. L. Ransome.[38] Another point which is of equally great importance lies

[38] *Loc. cit.*

in the ability to foretell to what depths the secondarily enriched zones are likely to persist. In other words, some minerals retard the process and cause shallow zones of bonanza ore, while other minerals exert little or no effect, and the zone is then apt to be more extensive and contain lower grade ore.[39]

To start the process, pyrite or some other iron sulphide must be present in the ore, for by its oxidation, ferric sulphate and sulphuric acid, the potent solvents of the sulphides, are derived. With iron sulphide scarce or absent, native silver will be expected in the gossan, and there will be little or no enrichment; with iron sulphide abundant, there will be little native silver in the gossan and greater enrichment.

If the halogens are present in the mine waters, they will precipitate the minerals cerargyrite, embolite, bromyrite and iodyrite. These minerals appear to be stable in the presence of sulphuric acid and ferric sulphate and consequently remain in the upper portions of ore deposits, giving a considerable enrichment at or near the surface. Deposits of this type are best developed in arid regions and occur in the Great Basin region of the west.

In deposits, containing the "active" minerals, alabandite, chalcocite, tetrahedrite, pyrrhotite, niccolite, smaltite, covellite, tennantite, and siderite with sulphides shallow zones of enrichment are to be expected. Among the common sulphides which may be associated with the silver minerals and which exert a slower precipitating effect may be mentioned chalcopyrite, sphalerite, galena, stibnite and pyrite.

Examples in which the above discussed processes have influenced the deposition of secondary silver minerals are numerous, and only a few need be cited here. At Cobalt,[40] Ontario, the principal sulphides include smaltite, cobaltite, cloanthite, niccolite, and bismuth sulphide with some arsenopyrite and tetra-

[39] Emmons, W. H., "The Mineral Composition of Primary Ore as a Factor Determining the Vertical Range of Metals Deposited by Secondary Processes," Congrès Geologique International, Twelfth Session, Toronto, 1913, pp. 261–269.

[40] Miller, W. G., The Cobalt Nickel Arsenides and Silver Deposits of Temeskaming," Rept. of the Bureau of Mines, vol. 14, part I., Toronto, 1913.

hedrite. Pyrite is rare. The ore minerals are native metal, argentite, proustite, pyrargyrite and dyscrasite. The gangue includes quartz and calcite. Extending downward 200 to 300 feet below the surface are rich silver minerals, largely in veinlets in earlier sulphides. The change from rich to low grade ore is very abrupt both in depth and along the strike. Van Hise[41] and Emmons[42] have attributed these richer silver ores to processes of sulphide enrichment, but Miller[43] believes that this feature of the genesis has been over-emphasized. The precipitation of the silver could have been accomplished by the niccolite, smaltite and cobaltite in the ore.

At Wood River, Idaho, according to Lindgren[44] the ore consists of galena, zincblende, and tetrahedrite, with but little pyrite and chalcopyrite; the gangue is siderite, or intermediate calcium, iron and magnesium carbonates, with a little quartz. Among the ore minerals, tetrahedrite is the principal carrier of silver. The ore shoots are markedly irregular. A marked deterioration may often be observed in depth; the large bodies of rich silver ore are found comparatively near the surface. The upper, oxidized parts of the veins are enriched by secondary silver chloride, native silver and pyrargyrite. In the tetrahedrite-rhodochrosite veins at Lake City, Colorado, according to Irving and Bancroft[45] the ores contain mainly galena, pyrite and tetrahedrite, the last rich in silver, with some pyrite in a gangue of quartz, barite and rhodochrosite. The precipitation of native silver in sideritic-sulphide ores at the Caledonia mine in the Coeur d'Alena has been mentioned. The ores of the same mine according to O. H. Hershey[46] contain tetrahedrite, some of which

[41] Van Hise, C. R., "The Ore-Deposits of the Cobalt District, Ontario," *Jour. Canadian Min. Inst.*, vol. 10, 1907, pp. 45–53.

[42] Emmons, S. F., "Cobalt District, Ontario," *Min. and Sci. Press*, March 18, 1911.

[43] Miller, W. G., "Notes on the Cobalt Area," *Eng. and Min. Jour.*, vol. 92, 1911, pp. 645–649.

[44] Lindgren, W., "Wood River Mining District," Twentieth Ann. Rept., U. S. Geol. Survey, pt. 3, pp. 218–231.

[45] *Loc. cit.*

[46] Hershey, O. H., "Genesis of the Lead-Silver Ores in Wardner District, Idaho," *Min. and Sci. Press*, June 1, 8, 15, 1912.

is said to assay as high as 3,000 ounces of silver per ton. In these districts tetrahedrite was undoubtedly the active precipitant of the silver, although at the Caledonia mine, siderite may have aided.

In deposits in which chalcocite is the chief ore mineral, a concentration of silver is usually found at the top of the chalcocite zone.[47] Abundant pyrrhotite would also halt the downward migration of silver very effectively, but there are few important pyrrhotitic deposits that carry much silver. The primary ore, at Ducktown, Tenn., carries only a few cents to the ton, but some of the ores of the secondary chalcocite zone carried more than .5 per cent. of silver. Pyrrhotite is abundant in the primary ore.

Among the deposits in which the processes of secondary sulphide enrichment have been effective, and have resulted in deeper zones of enrichment, may be mentioned the Granite-Bimetallic at Phillipsburg, Mont., and deposits at Georgetown, Creede and Aspen, Colo. At the Granite-Bimetallic mine,[48] the primary ore consists of quartz and rhodochrosite with pyrite, arsenopyrite, galena and tetrahedrite, and at several places abundant zincblende in the primary ore, below the richer sulphides. No pyrrhotite was noted. Rich ore with secondary cerargyrite, native silver and ruby silver in cracks across the older sulphides appeared in considerable amount 200 to 400 feet below the surface and extended to depths of 800 or 900 feet. At the Comstock Lode[49] some of the great bonanzas extended to a depth of 2,000 feet, but to what extent they are secondarily enriched is not certain. The ore consists of quartz with some calcite, in places banded with pyrite, galena, chalcopyrite, zinc blende, and finely distributed rich silver minerals, mainly, argen-

[47] Emmons, W. H., "Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold-Deposits," Ore-Deposits, A. I. M. E., 1913, p. 789.

[48] Emmons, W. H., and Calkins, F. C., "Geology and Ore Deposits of the Phillipsburg Quadrangle, Mont.," Prof. Paper U. S. Geol. Survey, No. 78, 1913, p. 202.

[49] Becker, G. F., "Geology of the Comstock Lode and the Washoe District," Mon. U. S. Geol. Survey, vol. 3, 1882.

tite, stephanite and polybasite. The occurrence at Georgetown where good ore extended locally down to 700 or 800 feet, and in the Colorado Central and to a minor extent in other veins down to 1,000 feet, have already been cited.

At Aspen, Colo., Spurr[50] differentiates the deposits into three classes—(1) barite veins, (2) silver sulphides, sulphantimonites and sulpharsenites, (3) galena and zincblende veins. The barite veins are generally barren. After their development rich sulphides, such as argentite, polybasite and tetrahedrite were deposited. A remarkable shoot of polybasite ore yielding many million dollars was mined in the Molly Gibson mine, at a depth of a few hundred feet below the surface. At Aspen, native silver has a wide range and is abundant in fissures and vugs of limestone and shale 900 to 1,000 feet below the surface and is distinctly later than the primary lean galena-zincblende ores.

In conclusion, the writer wishes to thank Prof. W. H. Emmons and Prof. F. F. Grout for their many helpful suggestions and indispensable aid during the progress of this work and the preparation of this report.

[50] Spurr, J. E., "Ore Deposition at Aspen, Colorado," ECON. GEOL., vol. 4, 1909, p. 301.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

EDITOR, ECONOMIC GEOLOGY:

Sir, The very interesting article by Dr. Howe, entitled "Petrographic Notes on the Sudbury Nickel Deposits," in your number for September, 1914, confirms the theory of magmatic segregation as accounting for those deposits, but suggests that the segregation took place in the original reservoir and not in the laccolithic chamber, as most geologists have supposed. This variation would, in his opinion, "relieve the theory of magmatic origin of the burden of many troublesome problems in physics and chemistry."

Though the modified theory is attractive and falls in line with the origin suggested for some other ore deposits, *e. g.,* the iron ores of Kirunavaara, there are serious difficulties in its application to the Sudbury region. These have been overlooked by Dr. Howe, probably because of the shortness of his visit to the district; and it is perhaps worth while to point out the features of these ore deposits which conflict with the new form of the theory.

Dr. Howe's excellent account of the ore-bearing norite at Frood corresponds with my own observations, but his conclusion that "although the megascopic appearance of the Frood rocks suggests that the sulphides and silicates formed contemporaneously . . . the magmatic origin of the sulphides can neither be proved nor disproved by thin sections" hardly seems warranted. He has shown that there is no evidence of replacement in the

ore enclosed in the rock, and if there is no replacement then the only other theory, that of magmatic segregation, is strongly supported by his observations. If his caution is due to the fact that the rock shows evidence of dynamic metamorphism, his doubts may easily be removed by studying exactly similar pyrrhotite-norite from other mines in which the ore blebs are enclosed in fresh norite where even the hypersthene is unchanged.

Dr. Howe's description of the relations at Creighton differs widely from the results of my own prolonged studies of that mine, and it is probable that conditions are now less favorable for investigation than in earlier days. The account of the contact of ore and norite and the figure showing norite fissured and crumbling at the edge suggest the usual relations of the ore to blocks of an older norite than the nickel-bearing rock. When mapping the mine on a large scale for the Canadian Copper Company some years ago, it was found that large angular or rounded masses of the older rock occur in both ore and pyrrhotite-norite; and it may be that an unusually large block has been taken for the hanging wall.

There is no doubt whatever that in the original open pit ore containing minerals belonging to the norite adjoined pyrrhotite-norite crowded with ore blebs, and that the latter diminished in number as one went away from the edge and were finally lost at some hundreds of yards distance. Though the old hanging wall has been removed in later mining operations there are still many tons of typical pyrrhotite-norite lying on the dumps near the mine. The members of the Geological Congress had no difficulty in getting good specimens of this rock intermediate between ore and norite, and characteristic suites of specimens illustrating the successive changes may be seen in our collections at the University of Toronto. It may be added that pyrrhotite-norite intervenes between ore and barren norite at all the other marginal mines of the region and that usually the fixing of the hanging wall of an ore body depends on the percentage of nickel and copper in this transition rock.

Dr. Howe cites in opposition to the usual magmatic theory the

numerous inclusions of micrographic quartz and feldspar in the ore, suggesting that they have been derived from the underlying granite and hence are not evidence of magmatic segregation. In reply to this it may be mentioned that none of my thin sections of the foot wall granite or gneiss show any micropegmatite except one from a thin selvage where granite and norite meet; while all my sections of Creighton norite contain quartz and micropegmatite in considerable amounts. An analysis of the rock shows that it is unusually acid, containing 60.15 per cent. of silica and about 3 per cent. of potash and soda. The finding of micropegmatite in the ore is then more favorable to the original magmatic theory than to Dr. Howe's modification of it.

However the most serious objections to this ingenious theory are derived from the field relations rather than from the use of the microscope. As mentioned before, pyrrhotite-norite is invariably found above the ore bodies in the marginal mines, and the enormous volume of this rock, running into cubic miles, is quite unaccountable if the ore was segregated before the norite reached its present position. These completely enclosed blebs of sulphides are like the shots of matte in slag where cooling has advanced too rapidly to allow of complete gravitational separation. The pyrrhotite-norite probably contains as much ore as all the mines of the region, and if half of the sulphides of the original magma are still enclosed in the rock is it probable that the other half lagged behind and came up after the norite had cooled and solidified?

Again, the marginal mines always lie in original hollows of the country rock and no important body of ore has been found enclosed in the norite. If this rock was solid before the influx of the ore one sees no reason why it should not sometimes have been fissured and penetrated by the liquid ore.

The offset mines, which are sometimes 3 or 4 miles from the edge of the norite, come nearer than the marginal mines to the conditions supposed by Dr. Howe; but even in the most remote of them there is always some norite or pyrrhotite-norite present, proof that the separation of ore and rock was not complete,

though the greater fluidity of the sulphides allowed them to enter small fissures in the country rock more easily than the somewhat less fluid norite. If the separation of the sulphides had taken place in the original magmatic hearth one would expect unmixed ore to reach the offset deposits and norite should not be found in them.

The usual form of the magmatic segregation theory accounts naturally for the important relations just referred to and also for the fact that the largest ore bodies occur at the base of the thickest portions of the eruptive sheet. The weight of evidence therefore favors the original form of the theory and not the proposed modification of it.

A. P. COLEMAN.

ASSOCIATION OF ALUNITE AND PYROPHYLLITE.

Sir:—In the January, 1915, number of ECONOMIC GEOLOGY, there appears an interesting article by Charles H. Clapp on alunite and pyrophyllite found on Vancouver Island. Clapp describes these minerals as occurring in Jurassic and Triassic volcanic rocks, chiefly fragmental, near dikes of quartz-diorite which appear to be apophyses of a grandiorite batholith.

In this connection it may be noted that a somewhat similar association of alunite and pyrophyllite was described by myself some years ago, the locality being the buttes known as the Tres Cerritos in Mariposa County, Calif.[1]

At the Tres Cerritos the rock containing the alunite and pyrophyllite is a greenstone-schist, a dynamo-metamorphic andesite-tuff, associated with black clay slates which are pretty certainly the Mariposa slates of lower Cretaceous or Jurassic age. Not far west of the Tres Cerritos there is an intrusive area of a dioritic rock of the grandiorite series, which has formed a contact-zone of chiastotite-schist in the surrounding clay states.

Thus in both Vancouver Island and the California occurrence the minerals are found together in old Mesozoic volcanics near

[1] Seventeenth Annual Report U. S. Geol. Survey, part I., p. 685. *Am. Jour. Sci.*, 4th ser., vol. 5, 1898, pp. 424-425. Bull. 511, U. S. Geol. Survey, p. 49.

granodiorite, although in neither case is there evidence that the solutions and vapors which formed the minerals, owe their origin to the granodiorite magma. Indeed Clapp considers the alunitization and pyrophyllitization of the volcanics, although restricted to the neighborhood of dioritic dikes, to have occurred before the intrusion of these dikes, during the volcanic period. The alunite Kynchot Sound is given as natro-alunite, while that of the Tres Cerritos contains K_2O 4.48 per cent. and Na_2O 2.78 per cent. In both cases the alunite is associated with quartz.

In bulletin 225 U. S. G. S. George I. Adams describes the Rabbit Hole sulphur mine situated near the Western Pacific R. R. in Humboldt county, Nevada. Adams found that "In cavities of the rock formations carrying sulphur, there is a considerable amount of white pulverulent material which on chemical examination proves to be alunite." In 1913, in a visit to the Rabbit Hole mine, I noted a brownish compact substance filling a fissure in conglomerate beds a little northerly from the main mine workings. This conglomerate is supposed to belong to the Truckee Miocene. Suspecting the brownish substance to be alunite, I submitted a sample to chemist Jas. W. Howson of Berkeley who determined it to be alunite. The vein was fifteen inches wide.

H. W. TURNER.

REVIEWS

Leitsätze für die praktische Beurteilung, zweckmässige Auswahl und Bearbeitung natürlicher Bausteine. By J. HIRSCHWALD. 36 pages with 18 text figures. Gebrüder Borntraeger, Berlin, 1915.

In this booklet of 36 pages the author presents guiding principles in the practical examination and the proper selection and preparation of building stone. The text is virtually a summary of the results of the author's extensive studies of building stones and makes a valuable supplement to American text-books on the subject. It should prove a handy reference for everyone interested in the use of building stone.

There are seven chapters. In Chapter I. the textures of different rock types are explained, and the weathering qualities of the different rock forming minerals and cementing materials described. In Chapter II. the author discusses the practical examination of stones according to visible characters, and gives in summary form for each rock type the essential and accessory minerals, favorable and unfavorable properties of the stone, and the favorable and unfavorable modes of occurrence in quarries. In Chapter III. he lays stress on the importance of the study of quarries, and points out the insufficiency of samples, especially of sedimentary rocks, in giving an adequate idea of the adaptability of a stone for different uses. He gives lists of the items to be noted in the study of quarries of sedimentary and igneous rocks. In Chapter IV. he discusses the significance of the following tests: determination of toughness, mineral composition and texture, porosity absorption and saturation, degree of softening in water, and resistance to abrasion. It may be said here that the last two tests are too often neglected in America. Resistance to abrasion is the most important property of stones to be used as tiles, steps, curbing, flagging, and paving, but only a very few test data on abrasion are recorded for stone, except those tested as road material by the Office of Public Roads. The many examples in the larger cities of the country of unevenly worn floor tiles and steps is further evidence of neglect to consider the abrasion-resisting qualities of stone.

Chapter V. is a very instructive discussion of the preparation and use of stone with reference to its bedding and cleavage. Stones of all kinds are divided into seven classes according to the ease with which they are split, and it is shown how stones should be laid and what classes of stone should be avoided in the building of different structures such

as massive walls, arches, columns, balustrades, etc. Chapter VI. is devoted to the selection of stone for different kinds of structures, and contains tables showing, for each kind of stone, the lowest softening coefficient and the highest saturation coefficient permissible for such different uses as cornices, sculptured stone, and stone courses close to the ground. The final chapter, VII., calls attention to control of diminution of the available stone supply, a feature complementary to the selection of first class material. The data in preceding chapters are cited as means of determining for what purposes each bed or layer in a quarry is adapted, and the producer is urged to quarry accordingly, reserving for certain purposes beds especially adopted for those purposes and using other layers for structures of less specialized requirements.

G. F. LOUGHLIN.

SCIENTIFIC NOTES AND NEWS[1]

DR. JOSEPH E. POGUE, associate professor of geology at Northwestern University, has gone to Colombia, South America, to carry on geological work in the Andes near Bogota.

THE SUMMER MEETING of the Geological Society of America is now in session at the University of California and Leland Stanford, Jr. University. Sessions are held in affiliation with the American Association for the Advancement of Science.

THE PRODUCTION of radium from Colorado carnotite ores by the Bureau of Mines in connection with the National Radium Institute has passed the experimental stage and is now on a successful manufacturing basis. The radium has been produced at a greatly decreased cost over other processes. A bulletin giving details of mining, concentration and methods of extraction is being prepared by the Bureau of Mines and will be issued early in the fall.

THE TWENTIETH annual meeting of the Lake Superior Mining Institute will be held on the Gogebic range September 6, 7, 8, and 9. One day is to be spent on the Cuyuna range.

A. C. LANE, formerly state geologist of Michigan, is making a geological examination of the Indiana Mine in the Michigan copper region.

AT A MEETING of the Royal Society of Canada Mr. J. B. Tyrrell, of Toronto, read a paper entitled Pre-Cambrian Goldfields of Central Canada, an abstract of which will appear in No. 5 of ECONOMIC GEOLOGY.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.